the Pa the Stars

Willem J. Luyten

Carnegie Grant

THE PAGEANT OF THE STARS

Photograph Harvard Observatory

PLATE I

The Large Magellanic Cloud, an island universe in miniature, and the nearest neighbor of the Milky Way system. It is 100,000 light years distant, and contains millions of stars, many nebulæ, star clusters, and variable stars. Although its southern position in the sky makes it invisible in our latitudes, it is a conspicuous object south of the equator.

THE PAGEANT OF THE STARS

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To

EJNAR HERTZSPRUNG

Whose penetrating insight first perceived the light that has guided the astronomers of to-day through the darkness of the universe.

Sic iter ad astra

TABLE OF CONTENTS

LIST OF PLATES

LIST OF FIGURES

INTRODUCTION

"'And who the deuce was Pythagoras?'
"'A sage who held that the earth is round and that it moves round the sun.'
"'What an utter fool! Couldn't he use his eyes?'"
—SHAW.

MAN cannot live by faith alone. Surrounded as he is by a world of facts, he seeks knowledge and understanding of these facts. On a knowledge of facts, however imperfect, man must build the superstructure of faith. His knowledge represents his determination to be fully conscious of the material universe; his faith represents his desire to be at peace with the spiritual universe. Civilization is man's effort to achieve such knowledge and to attain such faith. In the pursuit of these ends astronomy plays a unique and significant part, since it is the only science that deals with the material reality outside this earth.

Astronomy was born out of wonder at the mystery of the dark and starlit night, wonder at the countless host of stars, so familiar and yet so remote; that wonder which Plato called the soul of science. Emerging from this primitive wonder, astronomy has matured down the centuries, widening

its scope as man's mind turned from itself to press on in its bold and undeterred quest of the boundaries of his universe, boundaries which have now receded so far that his knowledge of fact and his exercise of faith unite to set his finiteness in infinity.

Consequently, advance in astronomy is a phase of the advance of civilization—as man's outlook grew less parochial astronomy progressed from an anthropocentric to a geocentric point of view. At this stage it was sufficiently dominated by the authority of Aristotle, lingering throughout the Middle Ages, and by ecclesiastical interpretation of the Scripture, to postpone all further development until the general intellectual awakening of the Renaissance. It is no mere coincidence, therefore, that we find the formulation of the new truth in astronomy taking place simultaneously with the struggle for new ideas in religion. In 1512 Copernicus first published his views on the rotation of the earth and the central position of the sun in the planetary system—five years before Luther's dramatic gesture at Wittenberg. Copernicus's heliocentric system led to Newton's discovery and demonstration of the principle of universal attraction, and with this first expression of a perfect law of nature it may be said that astronomy came of age as a science. In the meantime the telescope had been invented, and its introduction into astronomy, coupled with Newton's law, entirely changed the aspect of our science. Naked-eye astronomy ceased to exist, the universe became increasingly

telescopic, and as a natural consequence astronomy developed into a pure science, thus severing its connection with the theological view of creation. The next century saw the development of celestial mechanics and with it the desire to inquire into the motions of stars and planets; researches into the structure and the mechanism of the cosmos supplanted the former simple description of the visible heavens. Astronomy to-day is almost exclusively telescopic, the naked-eye stars constitute considerably less than one millionth part of those that are now visible in our largest telescopes; the discovery of thousands of island universes and the introduction of the doctrine of relativity have entirely changed the concept of space. But in all this tremendous development we find unity: matter is the same everywhere, chemical elements, atoms, and electrons are the same in the stars and nebulæ as on the earth, and they obey the same laws everywhere.

Through the introduction of giant telescopes and of photography, and through the application of modern physics and chemistry, new vistas have been opened far beyond the wildest dreams of our predecessors. At the same time, astronomy, though grown more diversified, has yet preserved the unity of its basic truths. To-day more than ever before we stand silent in admiration before the truths unveiled by astronomy, before the unity of fact throughout creation.

Chapter I

THE ORIGIN OF THE SOLAR SYSTEM

"Parturiunt montes, nascetur ridiculus mus."
—HORACE.

MILLIONS of millions of years ago our sun was travelling through space—alone. It was still a young sun, much more brilliant and much larger, and quite alone, having no attendant planets. Then, out of the millions of other stars, one seemed to single itself out. The others all appeared to move haphazardly, approaching the sun for a while, passing at a considerable distance, then losing themselves again in the depths of space; this one star, however, appeared to aim straight for the sun. For thousands of years it approached, and there seemed no doubt but that the sun and this star were destined to meet, both driven helplessly down their courses by the force of gravitation. In the eternal silence of empty space these two denizens of the universe were hastening toward their inevitable cataclysm, unwatched by witnesses, unconscious of their surroundings. As they continued to approach, their mutual attraction began to make itself felt, for not

only did they both acquire greater and greater speed, while at the same time curving into one another, but, both being gaseous, they raised huge tides on each other's surface. Both assumed a pearlike shape, their speeds increased to a hundred miles a second or more, and still they approached. Then, when the fateful hour had struck, the stems of the two pear-shaped bodies melted into one another, the stars were thrown into convulsions, and a desperate combat ensued, with each star trying to battle its way to freedom and attempting to get away again with all its belongings.

Here Nature stepped in and came to the rescue: for the very force of attraction that had made them melt into one another was also the source of their enormous speeds, and it was their terrific velocities that enabled them to separate again. The connecting link could not stand the strain and pull resulting from these great speeds, it broke into a thousand fragments, and for a while the scene was one of turmoil. When the smoke cleared there emerged from the chaos two very much mutilated suns, each tenaciously clinging to thousands of small bits of matter, each in furious rotation and each trying desperately to escape from the scene of recent conflict as quickly as its great speed would carry it. As the two stars separated, each gradually established order in the nondescript mass of accompanying fragments, and out of this chaos of matter there rose, in the course of time, an orderly and well-regulated

system of one large, central body surrounded by a number of smaller bodies revolving about the former: the planetary system.

Such is the picture which the present-day astronomer and cosmogonist paints of the origin of the solar system. There were no eye witnesses of the event; the other star has become lost in the voids of infinite space during the millions or billions of years that have elapsed. Yet, the astronomer can reason back all this length of time, and from his knowledge of present-day facts of the solar system, and with the aid of his mathematics and physics reconstruct the major aspects of the cataclysm.

We have sketched the occurrence essentially from the point of view of an inhabitant of a planet. To such a being the effect on the sun of the disastrous visitor was indeed gigantic in proportions; from the sun's point of view, however, it was little more than a passing disturbance, an incident in its life which had but small lasting influence. After the other star had wandered away, things quieted down again and only those fragments that had gone too far, or had acquired too much speed, were able to maintain a separate existence. The majority of the ejected material dropped back again into the sun, and when stock was taken of the actual losses it was found that the losses did not amount to more than one per cent.

Before a theory of as great importance as this can be accepted it is always well to inquire whether

it is reasonable. By reasonable we mean not improbable. In other words, what are the odds that two stars do come close enough together to give rise to such great disturbances as the birth of a planetary system, and how does the theory fit in with our ideas about the age of the earth? We know that head-on collisions between two stars occur not much more often than about once in every trillion years for the whole universe. A close approach will be much more frequent, and especially in the denser parts of the universe it may well occur thousands or millions of times more often.

Geologists tell us that the earth's crust is probably more than one thousand million years and less than eight thousand million years old. On the other hand, mathematicians can arrive at an estimate of the time required to change the original chaotic state of the solar system into its present more orderly state. Jeffreys, in England, has calculated that this would take one thousand million years at the very least, and might well take much longer. Other estimates have been as high as eight, or ten billion years. Considering these excessively long times, it appears as if the odds are no longer against the theory, and herein really lies the *crux* of the whole matter: given time enough, almost anything may happen, and of time astronomers have plenty.

The theory as we have outlined it here is largely the work of four men: Chamberlin and Moulton

of Chicago and Jeans and Jeffreys of Cambridge, England, although the germ of the idea is already to be found in the writings of Buffon. The theory is by no means complete, and we must not expect it to explain everything. There are still many unsolved problems in the solar system, still many unanswered questions, and even some obstacles which, for the sake of the theory, we prefer to ignore at present. Taken on the whole, however, the Chamberlin-Moulton theory explains the salient points in the problem of the formation of the solar system, and meets with no direct contradictions. And this, after all, is about all we can ask of a theory of the genesis of the planets, an event which must have happened billions of years ago.

Previous to Chamberlin and Moulton, the "nebular hypothesis" of Laplace held the field against all others. According to this theory, the whole solar system once was an enormous nebula which, by some means or other, got into a state of rapid rotation. As time went on, the nebula shrank and thus increased its rapidity of rotation, until finally it threw off rings of matter. These rings were then supposed to condense and form planets, which in turn rotated and threw off smaller rings which formed the satellites. Unfortunately, it has been shown by recent work of Jeans on the behaviour of gases that such a nebula could not throw off rings, and that, even if rings were formed, they could never condense into a planet. And thus, in spite

of its otherwise attractive features, Laplace's nebular hypothesis has had to be abandoned; one serious objection was sufficient to kill it.

Returning once more to Chamberlin and Moulton's idea, or the hypothesis of "dynamic encounter," as it is called, we note that the chances for such an event to happen, though not prohibitively insignificant, are still small enough to render improbable the existence of large numbers of planetary systems. It is rather gratifying to our terrestrial vanity to be able to think that planetary systems are not common in the universe. We know of only one with any degree of certainty, viz., that one appertaining to the star that was so instrumental in the creation of our own. However, this other star, with its attendants, may now be in some remote corner of the universe, lost among its millions of neighbours, and, in spite of our curiosity, it seems unlikely that we shall ever be able to identify it.

Having explained why we are here, it is time to consider the question why we continue to be here, and to study the why and how of the motions of the planets and their satellites around the sun. The first desire for an explanation of these motions originated with the ancient astrologers who sought to use the change in position of the heavenly bodies for making forecasts concerning the weal and woe of humanity. From their point of view the planets and stars were mere puppets moved by the hands of invisible gods to indicate their wishes to the

human race, and it was therefore sufficient to find a descriptive explanation of the motions; the reason *why* never entered into the question. Considering that the world conception of the ancients was *geocentric*,[1] it is not surprising that the first systems proposed all postulated the planets moving in circles with the earth as centre. As observations became more precise this simple idea proved untenable, and complicated additions were made to it: the planets were now supposed to revolve in circles, called epicycles, the centre of which revolved in another circle around the earth as centre. This system was devised by Hipparchus and Ptolemy, and published by the latter in his *Almagest*, the great astronomical encyclopædia of antiquity. Having risen to its highest point in ancient times in this work, astronomy was left there for many centuries, partly because the Church of the Middle Ages, in its interpretation of the Scriptures could not allow the earth to be dethroned as the centre of the universe. And so long as the earth remained fixed in the centre of the universe no better interpretation of the motions of the heavenly bodies was possible.

Toward the end of the Fifteenth Century however, the power of the mediæval church began to wane. New thoughts and new ideas sprang up everywhere, not only in the arts, but also in science. In Germany these found their expression in the theories of Copernicus, who asserted that the earth

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[1] Earth as centre.

rotated on its axis, and that all the planets, including the earth, revolved about the sun. For various reasons Copernicus withheld his manuscripts from publication, and it was not until he lay on his deathbed, in 1543, that he saw the proofs of his work: *De Revolutionibus Orbium Coelestium.*[2] His cause was espoused in Italy by Giordano Bruno and Galileo Galilei, who, for this reason, were opposed by theologians and scientists alike. Galileo's treatise on the Copernican system was interdicted and it is interesting to note that this ban was not lifted until 1835. In Denmark Tycho Brahe fought the new system, and undertook a long series of accurate observations to prove it wrong. Tycho died before he could complete his work. His observations furnished Kepler with the means to prove that the planets move in ellipses instead of in circles around the sun, and to formulate his laws upon the rapidity of this elliptic motion—laws which were in direct contradiction to what Tycho had expected to obtain from his observations.

Thus far all explanations of the planetary system had been descriptive. It remained for Newton to formulate the simple law behind it all: the law of gravitation or universal attraction. With one stroke of genius Newton solved *all* difficulties of the planetary system. The enunciation of the simple but fundamental principle that all things material attract each other with a force proportional to their weight

[2] Concerning the Movements of the Heavenly Bodies.

and inversely proportional to the square of the distance between them sufficed to explain *all* motion. Copernicus's book appeared in 1543, Newton's *Principia* in 1687: in less than one hundred and fifty years astronomy had developed from a primitive, descriptive science to one which has found its fundamental law. It is true that Einstein's theory of relativity with its accompanying change in our physical and philosophical concepts has given us a new insight into the nature of gravitation, but its resultant change in the mechanics of the solar system has been practically nil. Except for a very small correction in one instance, Newton's law still holds in its entirety, and it stands to-day, as it did two hundred and fifty years ago, as the basic law of our concept of planetary motion.

Newton's law applied to the Copernican system gives a complete picture of the mechanism of the planetary system. It is shown that all planets must move in *ellipses*, with the sun slightly outside the centre. It might be well at this point to say that an ellipse is, roughly speaking, oval in shape, and it has two points in its interior called foci which have singular geometric properties; in the planetary ellipses the sun occupies one of these. These ellipses are all very nearly circular, their *eccentricity*, which determines the ratio of the greatest length to the greatest width, being very small, and for practical purposes we may well consider them as circles here. At present eight planets are known. In order of

	Mean Distance from the Sun		Period of Revolution (days)	Diameter (miles)	Mass (earth = 1)
	(Millions of Miles)	(earth = 1)			
Mercury....	36	0.387	88	3,030	0.034
Venus.......	67	0.723	225	7,700	0.810
Earth.......	93	1.000	365	7,918	1.000
Mars.......	142	1.524	687	4,230	0.106
Jupiter......	483	5.20	4,333	86,500	313.31
Saturn......	886	9.54	10,759	70,000	93.87
Uranus......	1,782	19.19	30,686	31,500	14.57
Neptune....	2,792	30.07	60,188	34,800	17.24
Sun........	....	....	....	865,000	328,160
Moon......	....	....	....	2,163	0.0124

their distance from the sun they are: Mercury, Venus, the Earth, Mars, Jupiter, Saturn, Uranus, and Neptune. In the table are given the most important things we know about them at present: their mean distance from the sun, in millions of miles and expressed in the distance sun-earth as unit; the times required to complete one revolution around the sun; their diameter in miles, and their mass in terms of that of the earth. In the last two lines of the table similar data for the sun and the moon are appended.

It is seen that the first four planets are all much smaller in size than the next four; in addition, they are much closer to the sun, forming, so to speak, the inner half of the solar system. Sometimes they are called the *terrestrial planets,* to distinguish them from the other four, the *major planets.* Between the orbit of Mars, the outermost of the terrestrial planets, and that of Jupiter, the innermost of the major planets, a large number of very small objects are situated, the minor planets or asteroids. At present already more than one thousand of these are known; however, they are of interest collectively, rather than as individuals.

A glance at the table reveals a regularity in the distances of the planets from the sun which can be expressed to a fair degree of approximation by a simple and curious series of numbers known as Titius's or Bode's law. If we write down the geometric series 3, 6, 12, 24, 48, 96, 192, add zero

to the beginning, then add 4 to each member, we obtain the new series 4, 7, 10, 16, 28, 52, 100, 196. Comparing it with the numbers in the third column of the table of elements for the planets, we see that the approximation is indeed fair. The number 28

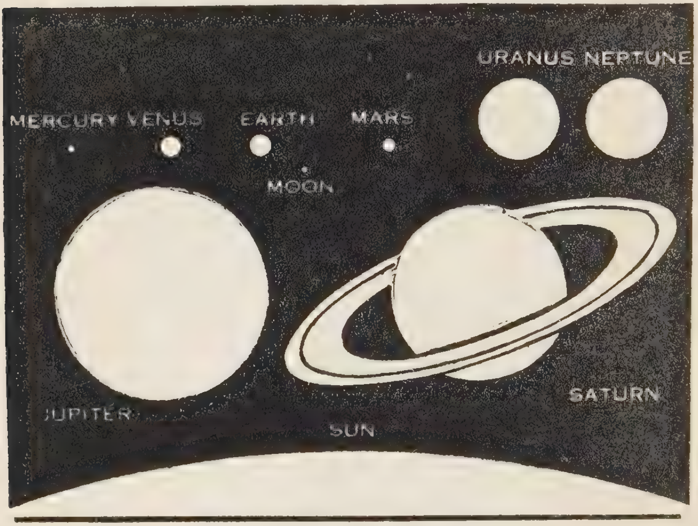


FIGURE 1.—RELATIVE SIZES OF THE SUN, THE EIGHT PLANETS AND THE MOON.

may be taken to represent an average minor planet, somewhere between Mars and Jupiter. It is not known at present whether this agreement is a mere coincidence or whether there is some law of nature, as yet not understood, behind it.

Looking through the table, we further notice that the combined mass of the eight planets is very

small compared with that of the sun. Undoubtedly, the total mass represented by the thousands or more minor planets is insignificant compared even with that of the planets. Practically the whole mass of the system, therefore, is at present concentrated in the sun. Reflecting on the past history of our solar system, however, it is surprising to find that more than half of the mass of what was once the solar system has now disappeared. The sun, we know, is radiating light and energy into space, but as a result of that, so relativity assures us, the sun is losing weight at the prodigal rate of more than two million tons a second. We have seen that the planetary system is probably about five billion years old, and the sun itself not less than a few trillion years. Furthermore, it is likely that the sun has kept on shining during all this time at least as brightly as at present, and probably increasingly so the farther back we go in time. A simple calculation then shows that the present mass of the sun is considerably less than that which it had at the birth of the planetary system, and probably less than half of that with which it was born. Thus, we may readily say that the larger part of the solar system has now ceased to exist: it has been radiated away into space.

Chapter II

THE EARTH

"... 'What makes me believe that nobody lives here,' said the Saturnian, 'is that it appears to me that common-sense people would not want to live here.' 'Well,' ventured Micromegas, 'perhaps the inhabitants lack common sense.'"

—VOLTAIRE.

FROM the point of view of the universe our sun may be only a second-rate star, and our earth only a second-rate planet of the sun. To us, terrestrials, the earth always will be the most important and the most interesting of all objects in the universe In describing it, the astronomer feels embarrassed by the wealth of material at his disposal; where to begin, and what to consider. There are so many points of interest that in most fields any discussion will soon lead into the borderlands of the various related sciences: geology, meteorology, geodesy. Most important of all to the living human being, the biological sciences have their say; even theology voices her claim to a place in the sun.

We have seen how the modern scientist visualizes the formation of the earth as an independent body,

as the outcome of a calamity which befell the sun between one and ten billion years ago. Thus the earth came into being, but it was then by no means fit to live on. For the first 15,000 years of its existence the earth was gaseous or liquid, and rotated on its axis in about four hours; the day and night at that epoch, therefore, were only two hours long. At the same time the earth had not yet quieted down, but was still contracting and expanding, vibrating so to speak, in a period of about two hours, while the sun was raising huge tides on it, with "high tide" twice a day, that is on the four-hour-day basis, every two hours. We all know what happens when we start a swing, and then give it a push every time it reaches its highest point: the length of the swing will become greater and greater. The same happened to the earth which, although liquid, was of a syrupy consistency. It was swinging in a period of two hours, and every two hours the sun gave it an additional impetus by means of the tides. Consequently high tide became higher and higher, until finally the top of the syrupy wave was racing around so fast, and creating such a strain, that a large piece broke off, left the earth, and henceforth pursued a separate path: the moon was born. After the earth had performed this duty it settled down to a more normal state, its temperature, which had originally been as high as 500 degrees, quickly dropped, enabling the crust to solidify, and water to condense and form the

oceans. The time elapsed since this process was completed has been estimated in several ways, but the most reliable method appears to be that which uses the breaking up of radioactive substances. You have undoubtedly heard of radium, used so much in therapeutics. To the chemist radium is just one of those ninety elements, those simplest of substances, from which everything is built up. These elements constitute the "bricks" from which the whole universe is made. When we list them in order of their weight, we find that radium, uranium, thorium, and several others, all of which occur at the heavy end of the list, are also the ones that decompose most easily. Being so heavy and complex, they seem to have taxed Nature's resources to the limit, they become unstable, and are slowly but constantly disintegrating. Give them time enough, and they will all turn into simpler elements, principally lead. The rate at which this decay goes on is controlled entirely by forces in the innermost part of the atom, so near the nucleus, and so well protected against outside interference, that nothing we can do to an atom of such an element in the laboratory seems to have the slightest effect. If we may then assume that such has been the case since the formation of the solid crust of the earth, we have merely to pick up a rock that contains uranium and radium, determine the amount of lead that has been formed in it, and we have its age, and with it the age of the earth's crust. Estimates

made in this way indicate that the solid crust of the earth is more than one billion but less than eight billion years old.

When it comes to describing the successive stages of evolution of the earth's surface since the formation of the solid crust, and through the early periods of life up to the present day, we should have to follow the geologist through his list of impressive names of the various periods of the development of the earth, names which, apart from their impressiveness, can have but little meaning for the uninitiated. Let us rather take the earth for granted, take it as it is to-day, with its solidified crust, its mountains, its oceans, and its atmosphere, and first consider its figure.

Far back in antiquity, and by all primitive peoples alike, the earth was supposed to be a flat disk. Some of the Greeks, however, held different views. Eratosthenes, who lived about 250 B. C., noticed that on the longest day of the year the sun cast no shadow at Syene, in upper Egypt, and was therefore straight overhead, while at Alexandria the shadow cast by the sun corresponded to a deviation of 7 degrees from the point overhead. Then, Eratosthenes reasoned, if the earth is a sphere, the distance from Syene to Alexandria, 500 miles, must be equal to an arc of 7 degrees on its surface, and the circumference of the earth must measure 25,000 miles: remarkably near the true figure. More precise measurements made in modern times have

shown that the earth is not a perfect sphere, but flattened at the poles, or an *oblate spheroid* as the mathematicians will have it. Its greatest diameter is at the equator, 7,927 miles in length, while the polar diameter is 27 miles shorter, totalling only 7,900. This flattening of the earth is not really conspicuous; on a terrestrial globe of one foot diameter the indentation at both poles would not amount to more than one-fiftieth of an inch. The highest mountain and the greatest ocean depth, both of the order of five or six miles, would be less than one hundredth part of an inch, and might be reproduced, on such a terrestrial globe 12 inches in size, by a change in the coat of varnish. Seen from a great distance, the earth would appear almost as smooth as a billiard ball.

Very recent, and sensitive measures have indicated that the earth is not even a perfect spheroid but an *ellipsoid*, with three unequal axes. There seems to be a slight bulge amounting to at most 200 yards along a certain meridian, with a corresponding deficiency along the meridian at right angles. Curiously enough, the meridian favoured by the bulge seems to coincide almost exactly with the meridian of Greenwich.

Using a very delicate pair of scales, the Eőtvős balance, physicists have been able to "weigh" the earth, by comparing its attraction to that of a large ball of lead or quartz, of known weight. Their answer is: six thousand million million million tons,

a 6 with 21 ciphers (6,000,000,000,000,000,000,-000). From the diameter given above we calculate that the total volume of the earth is 259,000 million cubic miles, then dividing this into the weight we find a density of 5.5, that is to say, taken on the average, the earth is five and one-half times heavier than water, almost as heavy as pig iron. Since the superficial layers of the earth are composed of rock, and are considerably lighter, having a mean density of only 2.7, it follows that the inner core must be much denser. This can be explained by the enormous pressures exerted by the outer layers on the inside, which pressure already amounts to 300 tons per square inch at a depth of only 100 miles.

The best way we have of determining what the interior of the earth is like, is by observing, by means of a seismograph, earthquakes at distant points. The different ways in which these tremors are transmitted along the surface and through the inner core of the earth make it possible for us to "see through" the earth; the earthquake vibrations constitute a sort of X-rays. The conclusion is reached that most of the inner part of the earth is more rigid than steel, although at the very centre it may be liquid in consistency. To this knowledge of the earth's interior, Jeffreys has added some data concerning the temperature, having found that where the increase in temperature is about 1 degree

centigrade for every 100 feet downward, layers deeper than 400 miles below the surface are still at practically the same temperature as when the earth was born.

A description of the earth would not be complete without mention of the blanket that protects us from the biting cold of empty space, the *atmosphere.* Near the surface of the earth this gaseous envelope is composed principally of two gases, nitrogen and oxygen, roughly in the proportion of 4 to 1, with slight additions of water vapour, carbon dioxide, and some of the lighter gases such as hydrogen and helium. As we ascend in this atmosphere, the heavier constituents, water vapour and carbon dioxide diminish rapidly, while the atmosphere as a whole is getting rarer and colder. At a height of 15 miles above the surface we have passed through all but 4 per cent. of the atmosphere, and yet we know that there is enough atmosphere left at heights of 100 miles or more, to produce white heat by friction in meteors speeding through it.

This is what we know about the earth itself, its origin, its constitution, and its surface conditions, and to us who live on the surface it is almost enough; to us the earth is the symbol of immobility. This tranquillity is only apparent, however, for to an onlooker in the universe at large this earth would present a spectacle of extreme restlessness, of almost distressing complexity of motion. Suspended in empty space, the earth would appear to be agitated

by a variety of forces, each of which made it move in a different path, with the result that the combined "true" motion would present so baffling a problem that its solution appears to contain insurmountable difficulties. First of all there is the diurnal motion, the rotation of the earth on its axis, to us the most important of all perhaps, since it gives us day and night and as such controls our mode of living, and almost all life on earth. From the point of view of explanation by mathematical formulæ it is immaterial whether we assume the earth as fixed, and make the sun, moon, stars, and planets revolve around us in twenty-four hours, or whether we ascribe the rotation to the earth. The former point of view was naturally taken by all primitive people, to whom the earth was the centre of the universe. When Copernicus dethroned the earth from this position, and postulated its rotation on an axis, the chief argument for his side was that it was far more probable that only the earth moved than that all the heavenly bodies together moved in unison. Later an experimental and absolutely convincing proof for the rotation of the earth was devised by Foucault and tried in 1851 in the Panthéon in Paris. His apparatus was quite simple and consisted of a heavy iron ball suspended from the ceiling of the dome of the Panthéon by a wire 200 feet long. The ball was set in motion by being pulled sideways and released, and allowed to swing freely. It was then noticed that the plane in which this pendulum was

swinging slowly rotated from east to west. A mathematician can easily prove that, once a pendulum is set in motion, and in the absence of external forces, the direction of its swing does not change; there is then but one conclusion to be drawn from Foucault's experiment, namely that *not* the plane of the pendulum but the floor under it was turning, and turning from west to east. In the rotation on its axis the earth carries everything on its surface around with it, and thus all objects on the equator cover a distance equal to the circumference of the earth, 25,000 miles, every day, corresponding to a speed of 17 miles per minute. This velocity diminishes as we go from the equator to the poles; in the latitude of New York it is only 11 miles a minute; at the poles themselves it is zero.

One of the greatest benefits we derive from the rotation of the earth is that it provides us with a clock, in fact with almost the only clock we possess. As space around us is empty, there is no friction, and we may expect the speed of rotation to be absolutely constant, in other words, the earth's rotation on its axis should constitute a perfect clock. This is indeed so; it is far more perfect a clock than any mechanical or electrical apparatus human intelligence has yet been able to devise. To a scientist, however, perfection is impossible to attain, and through an extremely long series of observations, carried to the limit of accuracy, astronomers have been able to discover that this "earth-clock" does

have its small imperfections. By comparing it with clocks based on the motion of the moon, on that of Mercury, and of the moons of Jupiter, slight irregularities in the behaviour of mother earth have been detected. Although we have no way of knowing if any of these other "clocks" are any more perfect than ours, we have to trust their larger number rather than their individual accuracy, for it would be absurd to suppose that all these other clocks were slow by the same amount at exactly the same time, and fast at some other time. The reason for this inconsistency in our rotational clock lies in the fact that the earth has not yet "set" completely. It is still contracting and expanding at intervals, and each slight change will either accelerate or retard the speed of rotation. The amounts of these changes, it should be added, are so small that they are of interest only to the astronomer. At present our day is getting consistently longer by about one thousandth of a second per century, while the total cumulative error of our clock due to the erratic changes will never be greater than twenty seconds at a time.

Another consequence of the oscillations of the crust of the earth is that the axis of rotation, although keeping the same direction in space, moves within the body of the earth. The poles therefore seem to wander over the surface; these wanderings can be very easily detected with our modern methods of observation, although, actually, they are

confined within a space smaller than the hall of Grand Central Terminal in New York City.

The second of the conspicuous motions of the earth is its motion around the sun. We have seen before how Newton's law of gravitation demands that every planet describe an elliptic path around the sun, with the sun in one of the foci. In the case of the earth the orbit is very nearly a circle, with the sun practically in the centre, and the distance between us and the sun varies but little, reaching its smallest value of 91.5 million miles in January, and its largest, 94.5 million miles, in July. As in the case of the earth's rotation on its axis, there is a direct proof in the present instance that it is the earth which is revolving around the sun, and not the sun around the earth, but this proof is based on the principle of the aberration and its explanation falls outside the scope of this book.

In our annual path around the sun, the axis about which the earth rotates remains parallel to the same direction in space. Since this axis is not perpendicular to the plane of the orbit, that is the plane of the ecliptic, each pole of the earth is alternately inclined toward the sun, or turned away from it. On June 21st the north pole is tipped toward the sun by its maximum angle, and receives sunlight during the entire twenty-four hours of the day, while the south pole is entirely hidden from the sun's rays. On December 22d the situation is reversed; at the intermediate epochs of March 21st and Septem-

ber 23d, the axis is inclined sideways, and both poles are equally illuminated, for both poles the sun is just visible on the horizon. As a result the day at the north pole lasts from March 21st until September 23d, the night from September 23d to March 21st.

At the equator, where every point is carried through the plane of the ecliptic twice a day, night and day are always of equal length, and there are no seasons. The angle between the axis of the earth and the perpendicular to the plane of the ecliptic, which angle is equal to that between the ecliptic and the equator, is 23½ degrees. If, then, we select a place on earth 23½ degrees away from the north pole, we see that on December 22d, when the north pole of the axis is tipped away from the sun by exactly that angle, the sun will no more than graze the horizon there; it will not really rise. On June 22d, on the other hand, the north pole is tipped toward the sun, and the sun, although it again grazes the horizon at our place of observation, is constantly *above* the horizon; it never sets. The circle drawn around the north pole at a distance of 23½ degrees therefore marks the limit of the "midnight sun," the period during which the sun does not set, increasing steadily from one night at the arctic circle itself to half a year at the pole. The phenomenon of the midnight sun is so strange that it is difficult to conceive an impression of it, without having seen it. In the regions north of the

arctic circle the sun may be seen crawling along the horizon, sinking into it almost imperceptibly, then rising again, and during the course of several hours around midnight the sun seems to follow along the horizon rather than move upward or downward.

We have stated that in its annual motion around the sun the earth kept its axis of rotation always parallel in space, but this is not strictly true. The earth, not being a perfect sphere but somewhat flattened, is subject to an extra attraction from the sun and the moon which tends to bring the planes of the equator and of the ecliptic into coincidence. It would long ago have succeeded were it not for the fact that the earth is rotating on its axis; the effect now produced is similar to that of a spinning top, rotating rapidly while its axis is being attracted toward the ground. It is a curious feature of the spinning top that, where the force of attraction is directed downward, its effect is acting sideways. We all know what happens in the case of the top; it begins to gyrate, that is, while it continues to spin around on its axis, this axis revolves, describing a cone, always making the same angle with the ground. Precisely the same thing happens to the earth, its axis of rotation gyrates very slowly, making one complete turn in 26,000 years, thus pointing to different directions in space but always making the same angle with the plane of the ecliptic. The direction toward which this axis points will always be, to us, the north pole of the sky, and thus we see

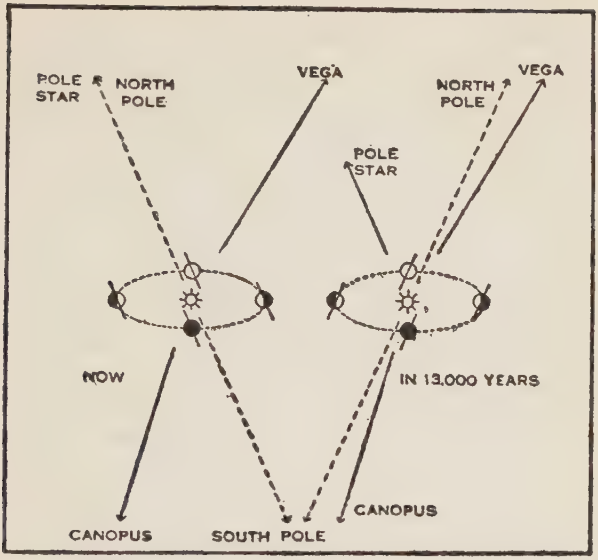


FIGURE 2.—SHOWING THE EFFECT OF PRECESSION, THAT IS THE MOTION OF THE AXIS OF THE EARTH AROUND THE POLE OF THE ECLIPTIC. THE DIRECTION IN THE SKY TOWARD WHICH THIS AXIS POINTS IS OUR NORTH POLE OF THE HEAVENS; AT PRESENT, AS INDICATED ON THE LEFT, THIS NORTH POLE COINCIDES VERY NEARLY WITH A BRIGHT STAR, WHICH THUS BECOMES OUR POLE STAR. IN 13,000 YEARS, HOWEVER, OUR PRESENT POLE STAR WILL STILL BE IN ESSENTIALLY THE SAME POSITION IN THE SKY, BUT THE AXIS OF THE EARTH WILL BE DIRECTED 47 DEGREES AWAY FROM IT, AND APPROXIMATELY TOWARD VEGA IN THE NORTH AND TOWARD CANOPUS IN THE SOUTH.

that, as a result of the gyration, or *precession* as astronomers call it, the north pole of the heavens moves among the stars. Our present pole star will not always be that—it will yield its place to others: in 6,000 years the star Alpha of the constellation Cepheus will guard the north pole, in 12,000 years Vega, the brightest star of the northern sky, will shine at the top of the vault of heaven, as it did 14,000 years ago, while in both instances Canopus, second only to Sirius in glory, hovered near the south pole. At the same time the part of the sky visible from any one spot on earth will change, new constellations will rise, and familiar ones disappear. The Southern Cross was visible all over the United States 6,000 years ago and will be so again in 20,000 years, while Sirius, the Dog Star, at present the glory of our winter nights, will disappear below the southern horizon 13,000 years hence.

While this is the principal motion of our pole, it is not the only one. The moon, revolving around the earth in an orbit which itself rotates, produces small oscillations in the precession of the pole. In addition, the moon displaces the earth to and fro out of its orbit in a period of one month, the angle between the plane of the ecliptic and that of the equator changes slowly, the whole of the earth's orbit is slowly and irregularly changed by the action of the planets. In this way we could go on almost indefinitely; with every refinement in observation and calculation a further source of change in the

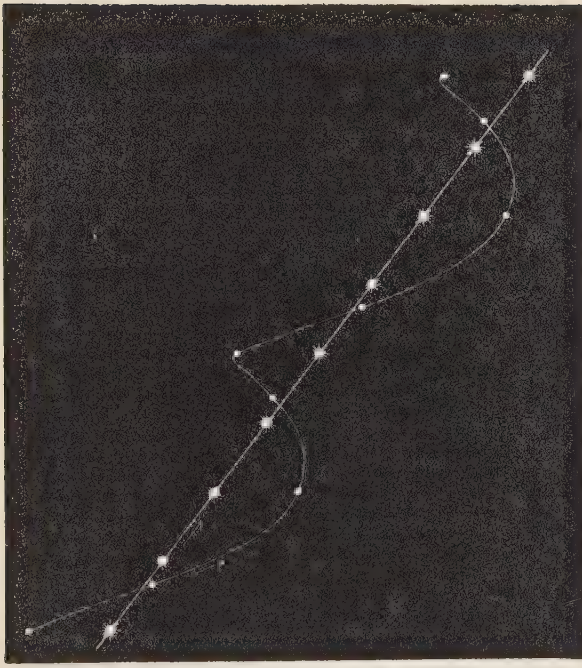


FIGURE 3.—THE REAL MOTION OF THE EARTH IN SPACE, AS IT WOULD APPEAR TO AN OBSERVER SITUATED IN THE DIRECTION OF THE CONSTELLATION, THE VIRGIN. THE TOTAL MOTION OF THE EARTH IS MADE UP OF ITS ORBITAL MOTION AROUND THE SUN, AND OF THE MOTION OF THE SUN ITSELF. THE POSITIONS OF EARTH AND SUN ARE INDICATED FOR INTERVALS OF THREE MONTHS.

position of the earth would manifest itself, until at length we should find ourselves with a combination of movements of such bewildering complexity as to defy understanding. However, it seems sufficient to indicate this type of involved mathematical calculation as an illustration of the intricacies of the problem, and of the hair's-breadth accuracy with which the modern astronomer analyzes the motions of the heavenly bodies. As such the problem is one rather for the advanced astronomer, and need not detain us here in our more general survey of the earth.

Chapter III

THE SUN

"At whose sight, like the sun,
All others with diminished lustre shone."
—CICERO.

FROM time immemorial the sun has been worshipped as the ruler of the sky, as the source of light and heat, as the originator and preserver of life, the symbol of ultimate and immaculate purity. Science, which has shattered so many idols of the past, has not only left the sun unmolested but has even exalted its significance. From a mere attendant of the earth, created for the benefit of the human race, the sun has been shown by astronomy to be the central and dominant body of the planetary system, dominating not only by virtue of its great mass, which forces all other objects in its vicinity to obey its will, but also because it is the only one that leads an independent existence, the only one shining by its own light.

Naturally, one of the first questions that comes to the mind is: how far away is the sun? Difficulties present themselves immediately when the astron-

omer tries to answer it. In space distances are measured by much the same methods which the surveyor uses in mapping out a piece of land, by selecting a base-line, the length of which is known with great accuracy, and by further measuring the directions of the various landmarks against certain fixed points on the horizon. Unfortunately, this method cannot give good results in the case of the sun, for when the sun is visible we can see no stars that could serve as fixed directions in the sky, and furthermore, the longest baseline available is at the most as long as the diameter of the earth, a paltry 8,000 miles. The astronomer, however, is resourceful, and takes to indirect means when direct methods fail him. Instead of measuring the distance from the earth to the sun directly, he first draws a map of the whole solar system, to scale, in which all distances are relatively correct, although not one of them is known in miles. He then selects the one distance which, for the time being, is the one most easily measurable, and in this way determines the scale of his picture and, indirectly, the distance sun-earth. From a variety of measures it has been found that this distance, which because of its great importance, in astronomy, is called the *astronomical unit,* equals:

92,870,000 miles.

To give a better impression of the immensity of this distance, we might add that it would take an automobile, going at the rate of sixty miles per hour,

175 years to reach the sun. Even a ray of light that can travel seven times around the earth in one second, requires 8 minutes and 19 seconds to bridge the gap between us and the sun.

From the sun's distance and from the size it appears to have as observed from the earth, we can at once calculate its actual size. It appears a trifle larger than half a degree in diameter, or about as large as a silver dollar at a distance of 14 feet; at a distance of 93,000,000 miles, half a degree corresponds to 864,000 miles, and this then is the diameter of the sun. Since the earth has a diameter of 7,900 miles, the sun is 109 times as large in diameter, 12,000 times larger in surface, and 1,280,000 larger in volume! If we represent the sun by a sphere, the size of a football, the earth would be no bigger than a large grain of buckshot, one tenth of an inch in size, and it would revolve about this football at a distance of more than 100 feet. Another way of illustrating the sun's enormous size is by stating that if the earth were exactly in the centre of the sun, the moon could still revolve around us at its distance of 240,000 miles and the entire operation be confined to the inner core of the sun; the moon would be only a little more than half way out to the surface.

As in the case of the earth, we cannot, obviously, weigh the sun directly, and we must calculate its mass from a comparison of the time it takes the earth to go round the sun, with the speed a stone

acquires during the first second of its falling to the ground: the same law of gravitation controls both motions. We find that the sun weighs 328,000 times as much as the earth, or, when expressed in tons, a 2 with 27 ciphers. From the sun's volume we then deduce that on the average the sun is one and one-half times as dense as water, and that, on its surface, the force of attraction is 28 times that on earth. A stone would fall 450 feet in the first second, and a mass of 70 pounds would weigh a ton on the sun.

When we turn a telescope on the sun, and study it in more detail, we notice that the surface, the emblem of purity for the ancients, is no longer immaculate, but that from time to time dark, irregularly shaped spots appear. These are known as *sun-spots,* and were first discovered by Scheiner, a Jesuit priest of Ingolstadt, Germany, and later confirmed by Fabricius in Holland, and Galileo in Italy. It seems, however, that the Chinese, although probably having no telescopes at their disposal, anticipated these discoveries, for the ancient chronicles testify that they observed a number of spots in the years from 300 to 1200 A. D. Seen through a large telescope, a sun-spot appears as a jet-black, irregularly shaped object, the *umbra,* surrounded by a grayish ring of cloudy appearance, the *penumbra.* In size the central core of the spot may vary from 500 miles to as much as 50,000 miles, or more than six times the diameter of the earth,

while the penumbra surrounding a group of spots may run up to 150,000 miles in diameter.

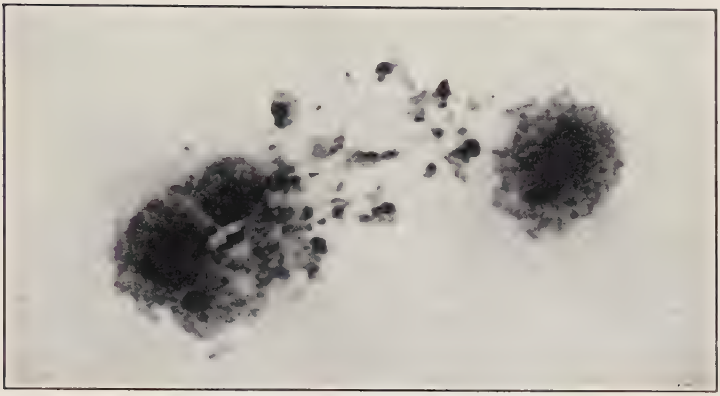
When sun-spots are observed from day to day it is soon noticed that they move from east to west across the sun's disk; this is simply a result of the rotation of the sun on its axis. The speed with which sun-spots move then forms a good means of determining the speed of the sun's rotation, provided we are sure that the spots remain fixed on the surface. Unfortunately, this is not so. By the time a spot has crossed from the eastern limb of the sun to the western, it may actually have moved on the surface itself, for we are, after all, not standing on rock bottom when we are dealing with sun-spots, but on a turbulent vortex of exceedingly hot gases. One peculiar thing about the sun's rotation is quite apparent; the sun does not rotate as a solid body, such as the earth. Here everybody, from pole to equator, is carried around with the earth once in twenty-four hours. On the sun, on the other hand, a spot near the equator takes 25 days to go round, while one near the pole would take almost 30. If we traced a straight line on the sun's surface from pole to pole, it would not remain straight, but look a corkscrew at the end of a year.

On the whole, sun-spots are short-lived, many of them lasting but a single day, and often the sun is entirely devoid of them. There is a certain regularity in their appearance; some years the sun seems covered with them, at other times we may scan the

sun's surface for days without seeing even one. They come and go in an eleven-year period; in 1917 their number was very large, while throughout 1923-1924 only very few were observed; 1929 will again see a maximum number of spots. The exact cause of this periodicity in the appearance of sun-spots is not yet known, although it has become increasingly evident, especially through the work of Hale at Mt. Wilson, that their origin must be deep-hidden, probably situated at considerable depth below the sun's surface.

A sun-spot is in reality a cylinder of hot gases shot up from the sun's interior and arriving at the surface while revolving at great speed. Naturally, when coming into the outer layers of the sun's atmosphere where the pressure of the gases is much lower, this whirlpool will expand and cool off. By cooling off it decreases in brilliance, and thus appears black, simply by contrast with the dazzlingly brilliant surface of the sun, although a sun-spot really is hotter than molten steel.

To an observer on the earth this is not all that sun-spots mean for him. They have a more tangible interest. Their influence is strong enough to reach across the gap of 93,000,000 miles and produce severe magnetic storms on the earth, or a magnificent display of northern lights. The connection between sun-spots and magnetism on earth has been proved beyond question through a comparison, made over a large number of years, of the number of sun-



Photographs Mount Wilson Observatory

PLATE II

Above: A typical sun-spot.

Below: The sun, photographed in hydrogen light, showing sun-spots, faculæ, and currents on the surface of the sun.

spots and the daily irregularities of the needle of the compass. Every time there is an abundance of sun-spots, disturbances of the compass are also frequent, while at the times when sun-spots are few and far between, the magnetic needle is quiet and regular. The reason seems to be that sun-spots themselves are strong magnets, and consequently appear always in pairs, though they may not always be visible as such. There are such things as invisible sun-spots, that only betray their presence when their light is examined in the spectroscope. Naturally, if a sun-spot is a magnet, we may expect that occasionally a very large and powerful spot may make its influence felt to a considerable extent all over the earth. Witness the occurrence of northern lights *(aurora borealis)*, which are nothing but manifestations from our upper atmosphere that it is receiving powerful electric blows from the sun. A large sun-spot almost invariably produces a strong display of northern lights about twenty-five hours after it has crossed the centre of the sun's disk, and if it is a particularly tenacious spot, it may come back again after the sun has completed one revolution on its axis, and produce another aurora. This happened, e. g., in January, 1926, when the same sun-spot came back four times and at its last appearance was still powerful enough to produce an aurora of great splendour, and to put the telegraph and telephone cables out of commission for several hours.

Sun-spots are phenomena of the sun's surface, usually called the *photosphere,* as are also the *faculæ,* bright streaks and patches of light often found to surround spots. Above the photosphere lies the sun's atmosphere, in its turn divided into two parts, viz., the *reversing layer,* composed of the vapours of many familiar substances, such as iron, calcium, sodium, and having a thickness of a few hundred miles, and the *chromosphere.* The reversing layer is so named because, being composed of gases at a much lower temperature than those in the photosphere, it absorbs a certain amount of light, according to the laws of optics, thus producing black lines. These lines are discovered when the sun's light is analyzed by the spectroscope. Above this reversing layer lies the chromosphere, composed principally of the lighter elements, such as hydrogen, helium, and calcium. It is from the chromosphere that the *prominences* rise, those great crimson flames of hydrogen which sometimes reach heights of hundreds of thousands of miles. Beyond the chromosphere extends the *corona,* the outermost thin, gaseous layer of the sun's atmosphere, thus far observed only at times of an eclipse of the sun. Both the corona and the prominences are extensively studied at such times, and we shall have occasion to refer to them later. The corona, though it may extend millions of miles outward, does not represent the farthermost boundary. Beyond it comes the *zodiacal light.* This may be seen on any clear,

moonless evening in spring as a faint glimmer of twilight extending upward along the ecliptic. In the tropics, or in Japan, when conditions are particularly favourable, the zodiacal light can be followed around the entire ecliptic, and there is but little doubt that it is caused by reflection of sunlight from a vast number of exceedingly small "dust" particles which seem to fill up all the space inside the earth's orbit, and even extend beyond it. From the total amount of illumination in this zodiacal light it can be calculated how many and how large these dust particles must be. We find that if the whole space between the sun and the earth is filled with particles one twenty-fifth of an inch in size, and twenty-five miles apart, the total light would be more than accounted for.

When the spectroscope came into use in astronomy, it became possible to study, not only the appearance of the sun's surface, but also its physical and chemical constitution, its temperature, and the behaviour of the gases in the surrounding atmosphere. While the observations stop at the surface of the sun, our minds can push farther, and with the aid of modern physical and chemical theories, and with what we know of the behaviour of atoms, we can penetrate deeply into the interior of the sun, where all its strange secrets are kept—"pluck out the heart of its mystery."

When sunlight is made to pass through a prism, a piece of glass with two edges not parallel to each

other, the light rays are deflected from their path. Rays of different colours are deflected by different amounts: blue light more than green, green more than yellow, and red light least of all. The result is that where a beam of white sunlight enters the prism, a band of coloured light emerges. On this rests the principle of the spectroscope. All we have to do is to put a photographic plate in this coloured band, and record the sun's *spectrum*. One of the first uses the observations of the sun's spectrum are put to is the determination of the temperature of the surface where the light comes from. Physicists have calculated that bodies of different temperatures give us spectra with different proportions of coloured light, and conversely, if we can measure the amount of heat contained in the green rays coming from the sun, as compared to the heat in the red or violet rays, we can tell the temperature of the sun. This has been done by Wilsing in Potsdam, and by Abbott of the Smithsonian Institution. They agree in putting the sun's temperature between 5,500 and 6,000 degrees centigrade, or about 10,000 Fahrenheit. Stating such a temperature as a mere number does not convey much meaning; perhaps a practical illustration is more to the point:

An interesting experiment was once performed by Langley in the steel works at Pittsburgh. As the molten steel cascaded forth from the Bessemer converter, lighting up the great room with a million

Roman candles, the intensity of its menacing glare was compared with that of the sun taken over an equal surface. It was found that the heat radiation of the sun was 87 times greater, while in light-giving power the sun surpassed the molten steel 5,000 times.

When the spectrum of the sun is analyzed more minutely, it is seen that it does not simply consist of a band of coloured light. On the contrary, this band is crossed by many dark lines, and these lines become more numerous as our apparatus for examination becomes more refined. We now know that each of these lines indicates the presence of a certain chemical element on the sun. The two strong lines far in the violet prove beyond question, for example, that there must be a considerable amount of calcium on the sun. A whole series of black lines running from the red to beyond the violet indicates the presence of hydrogen—lightest of all gases.

In the chromosphere the situation is slightly different; here the gases are observed, during a total eclipse of the sun, without any luminous background, and their characteristic rays of coloured light appear bright, instead of dark. One instance of identification of lines in the spectrum with a chemical element must be mentioned specifically: it concerns a bright yellow line seen in the spectrum of the chromosphere. There was no chemical substance known on earth that could produce a line in that exact place in the spectrum, therefore it was attrib-

uted to a new element, *helium* (so named after the Greek for sun). Later on, helium was found by Ramsay in the atmosphere of our own earth, and proved itself to be one of the most useful substances, lighter than any other gas except hydrogen, and non-inflammable; an ideal filling material for airships.

To realize fully the splendour of our sun we should obtain an idea of its prodigious output of heat, and to do this we must first go through some more cold analyses of scientific facts. Physicists have adopted as their unit of heat the *calorie,* the amount of heat which will raise the temperature of one gram of water by one degree centigrade. Accurate measures of the sun's heat, carried out by the Smithsonian Institution, have shown that every square inch of the earth's surface receives from the sun 12 calories every minute—and this at a distance of 93,000,000 miles! Therefore, the total amount of heat given off by the sun in one minute is equal to 12 calories multiplied by the number of square inches contained in the surface of a sphere with a radius equal to that of the earth's orbit: 93,000,000 miles. In this way we find that the total energy output of the sun exceeds half a million million million million horse-power, enough to melt a cube of ice 2,500 miles long, 2,500 miles wide, and 2,500 miles high every minute, and equal in one year to the heat produced by four hundred sextillion tons of the best anthracite coal. Before such staggering figures even the brain of a scientist reels, and we can but look up in

admiring wonder at this immense celestial furnace, to whose liberal expenditure of light, heat, and energy we owe our very existence.

How is it possible, one may ask, that the sun can go on dissipating energy at this rate, without burning out? The earth, we are told, has existed for well-nigh a billion years, and the sun must have been shining in full glory for a much longer time. How does it make up for the enormous loss of energy? Confronted with this problem the Mohammedan would exclaim: "Allah is great." The scientist will add: "True enough, but just how does he do it?" The first theory we had concerning this problem came from Helmholtz, who pointed out that, as the sun shrinks, it heats up because the gases in the outer atmosphere are falling in toward the centre. Unfortunately, however, later calculations showed that even if the sun had once been as large as the orbit of the planet Neptune, or 5,000,000,000 miles in diameter, it would have shrunk to its present size in less than 25,000,000 years. We have seen that the earth alone must have lived a great deal longer than that; consequently, Helmholtz's theory must be abandoned.

Again atomic physics has provided us with a closer-fitting explanation. Let us suppose that the interior of the sun, which is now believed to be several million degrees in temperature, is hot enough to effect a transformation of hydrogen into helium. In this process a certain amount of matter would

go to waste, since out of four pounds and one-half ounce of hydrogen we should get no more than an even four pounds of helium. Half an ounce of matter has disappeared, has "gone up in smoke." Not in "smoke," says the theory of relativity: this excess matter has simply been transformed into energy; heat and light, in other words. And "half an ounce of light" is a good deal, equal to about three billion kilowatts! Of course, we must remember that all this is a mere conjecture, we cannot place a thermometer in the inside of the sun and measure its temperature; we can use only our mathematical formulæ for this purpose. Nevertheless, we should not forget that the present theory is the only key to the mystery that we can now see; it may not be the correct one, but at least it explains satisfactorily how the sun has been able to live as long as it has, and it gives us a feeling of relief that, if the sun is really capable of doing this trick, it has obtained a new lease of life, and can go on shining for several billions and possibly trillions of years.

On the other hand, even though the sun has been granted a reprieve, the day of reckoning has only been postponed; the sun cannot escape its destiny. While our present-day theories may have succeeded in slowing up the grinding process of the mills of the gods, and consequently in lengthening the span of life of our sun, nemesis is bound to come. Ulti-

mately the sun will cool off and die. Life, such as we now know it, will long before have ceased to exist, though the planets themselves, like wandering tombs, will still be revolving around the sun in the oppressive silence of eternal night: spectres of the past, but perhaps—cradles of the future.

Chapter IV

THE MOON

> "Whilst she, in the vault of heaven,
> Moves with silent, peaceful motion."
> —HEINE.

THE moon is as old as the earth. It has been ploughing its way through space and has been a constant attendant of the earth for millions of years past. Its soft and silvery light had brightened our terrestrial nights long before there were human beings on earth to appreciate it. In all probability it was in the moon and its motion among the stars that astronomy and science found their first inspiration. From the moon the first calendars were made; on the moon and on its tide-raising effect the early seafarers depended. The sole reason for the high esteem in which the moon is held, is its nearness, not its inherent importance, for in space the moon is an insignificant object. In size it is no more than 2,160 miles in diameter, less than one third of the earth; in volume it is almost fifty times smaller, and in weight it is less than one eightieth that of our own planet.

Of all the heavenly bodies the moon is the nearest

to us, its mean distance from the earth being 240,000 miles, or only thirty times the diameter of the earth. We have to say "mean distance" here, for in its motion around the earth in 27 days, 7 hours, 43 minutes the moon does not always stay at the same distance. Like the earth in its path around the sun, the moon follows an ellipse, but a much more elongated one than that of the earth. While revolving in this ellipse, the moon rotates on its axis in exactly the same time, thus always presenting the same face to the earth. This is one of the tragedies about the moon: we have never seen the other side of it. It is no whim of chance that this is so, but a direct result of the way in which the moon was born, as Darwin has shown. When, under the attraction of the sun, moon and earth separated, they were both still in a liquid state, or at least in a state resembling a syrup in consistency. The moon, as we all know, is the cause of the tides on earth, but, conversely, the earth would, by reason of its greater attraction produce greater tides on the moon when the moon possessed oceans. At present the moon is all solid rock, but in the first few million years after its birth the moon was wholly liquid, and the earth raised huge tidal waves on it. Thus, while the moon was rotating on its own axis and revolving about the earth, the latter persisted in producing "high water," both in those places that were nearer and those further away. The moon, therefore, was never round, but always longer in the direction toward the earth,

and when it cooled off enough for parts of the surface to solidify, the solid part still tried to rotate on an axis in its own time, while the tides were running over the surface in the time demanded by the earth. Naturally, this caused great friction; the more the moon solidified, the more this friction increased until, finally, it became so great that the moon gave up the struggle, and meekly followed the time of rotation imposed upon it by the earth: twenty-seven days. Thus, for ages past, the moon has bowed to the superior will of the earth and always rotated on its axis in exactly the same time as it takes to revolve around us. To us on the earth this gives the appearance that the moon does not rotate at all, but this conclusion is a fallacy. It is much the same as when a man walks around a city square, always keeping his eye on a statue in the centre. Any observer standing near the statue would always see the pedestrian's face, and to him the latter would not seem to be turning. Yet any third person, standing outside the square, would immediately notice that in his walk around the square our pedestrian must face all directions of the compass, therefore he must be turning around—a rotation which consumes as much time as one complete turn around the square.

In the case of the moon, we do see a little more than half; this is owing to the fact that the moon's orbit is not entirely circular, and to certain slight irregularities in its motion. We can thus see about

59 per cent. of the moon's surface, the remainder being forever hidden from our view.

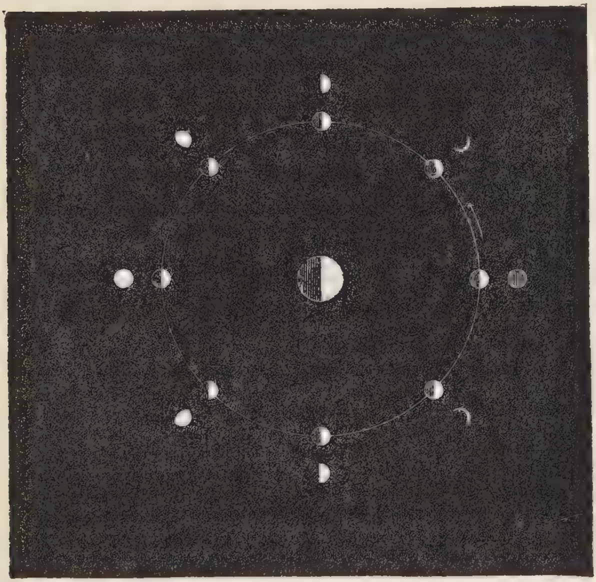


FIGURE 4.—THE PHASES OF THE MOON. EIGHT DIFFERENT POSITIONS OF THE MOON IN ITS ORBIT AROUND THE EARTH ARE SHOWN; WITH SUNLIGHT FALLING FROM THE RIGHT, THE MOON, AS SEEN FROM THE EARTH, WILL THEN APPEAR UNDER THE RESPECTIVE PHASES INDICATED OUTSIDE THE CIRCLE.

The moon is a cold and dark body, it gives no light of its own, and we can see it only because it is illuminated by the sun. That side alone of the

moon which is turned toward the sun is visible, therefore, how much we see of it then depends on the moon's position relative to the sun and the earth. When it is between us and the sun, we see nothing; it is *new moon*. When it is on the side opposite the sun, we see the whole disk illuminated; it is *full moon*. At all intermediate positions of the moon we see only part of its disk illuminated: a crescent when it is a small part, shortly before, or shortly after the new moon; or gibbous in appearance near the times of full moon; while at the times halfway between new moon and full moon exactly half the circle appears bright, the other half black. These are the *first* and *last quarters*. The moon is not a good mirror; it reflects only 7 per cent. of the incident sunlight. At full moon its light is 450,000 times fainter than sunlight; at first or last quarter it is more than 4,000,000 times fainter.

In 27 days, 7 hours, 43 minutes the moon completes one revolution about the earth; that is to say, as seen from a distant star, it would appear in the same position after that length of time. In the meantime, however, the earth itself has not been idle, and has advanced in its orbit around the sun by a considerable extent, with the result that the moon still has some distance to travel before it is again in the same position relative to both the sun and the earth. In our illustration above, this would correspond to the statue in the middle being put on a turntable and rotated very slowly. Suppose the

pedestrian started out facing north, and walked westward. By the time he was facing north again, he would have made one complete turn around the statue, as an outsider would see it. By that time, however, the statue would have turned enough to make the pedestrian go through till northwest before he would be in the same position relative to the statue. Seen from the stars, the moon revolves about the earth in 27 days, 7 hours, 43 minutes, but it takes more than two days longer, 29 days, 12 hours, 44 minutes, to cover the distance between one full moon and the next. Astronomers call the first time the *sidereal* period; the second, the *synodic;* it is this latter which is the basis of our month.

One thing on which we should lay particular stress is that the moon, while describing an ellipse around the earth, which itself revolves about the sun, follows a path that is always concave toward the sun. If we represent the orbit of the earth around the sun by a circle of seven feet in diameter, the moon would never deviate from this circle by more than one tenth of an inch on either side.

The moon's motion around the earth and the sun is only a first approximation; its exact motion is very complicated, as is that of the earth. In its orbit around the earth the moon describes an ellipse, and the longest dimension of this ellipse, the *major axis,* rotates in space, the shape of the ellipse also changing slightly. Next, we know that the plane of this ellipse makes an angle with the plane of the ecliptic,

and this angle varies somewhat, not only in amount, but in direction also, the moon being sometimes between the ecliptic and the equator, sometimes between the ecliptic and the pole. In this way, we could continue *ad infinitum,* for the number of intricacies in the motion of the moon is legion, making the whole problem resemble a "blindfolded chess game in three dimensions," as Professor Brown so aptly puts it. A fortunate occurrence, since this very complexity has caused the mathematical theory of such celestial motions to be thoroughly analyzed—a stupendous task, and one with which many of the great names in celestial mechanics are forever associated: Newton, Delaunay, Hansen, Poincaré, Newcomb, Brown, to mention but a few.

The weight of the moon may be found by various laborious processes, all of which involve a comparison of the respective attractive forces of the moon and the earth. The answer given by all of them is that the moon weighs less than 1/81 part of the earth. We know that the moon's volume is 49 times less than that of the earth; it follows that, volume for volume, the moon must be lighter than the earth and composed of materials that weigh on the average only three times as much as water instead of more than five times as much, as is the case of the earth. Thus, the moon weighs exactly the same as if it were composed of rocks similar to those we find immediately below the surface of the earth, which fits in well with the theory that the

moon came off the earth at the time everything was in a semi-liquid state. In that case the lighter materials would come off, while the heavier inner core of iron would remain with the earth itself.

The moon is so near that even the naked eye can see some detail on its surface, while an opera glass shows the darker areas in contrast to the whiter areas quite plainly. A small telescope, even as small as the first used by Galileo, reveals the mountains and the great plains and valleys; more powerful telescopes will show a wealth of detail. The naked eye sees the moon at a distance of 240,000 miles, or as large as a silver dollar at a distance of ten feet; the great telescopes on the Pacific coast bring it as close as 100 miles. With the 100-inch telescope at Mt. Wilson direct photographs of the moon can be taken which will show it with a diameter of 30 inches, or on a scale of 1:20,000,000. Such a photograph would stand considerable enlargement, and by means of such an enlargement we should be able to see things two miles in size. If, under favourable conditions, we looked through the telescope directly, we might see shadows cast by objects as large as the Great Pyramids or the Woolworth Building.

The more prominent mountain ranges, such as the Apennines, and the conspicuous circular craters of the type of Copernicus, Plato, Archimedes, are undoubtedly familiar to all who have ever observed the moon through a telescope of any size; we need not here fatigue the reader with an enumeration

of the mountains of the moon, which would simply be a catalogue of astronomers of the past. Lunar topography has offered unparallelled opportunities for immortality to astronomers who were of sufficient mediocrity to escape remembrance on earth; even after the great names of ancient and mediæval astronomers had been exhausted on the main points of interest, there was always a crater vacant on the moon, in desperate need of an insignificant name.

The mountains on the moon are relatively much higher than those on earth, for against a diameter of the moon, which is only slightly more than one fourth of that of the earth, the highest mountain on the moon is more than 22,000 feet high, not much inferior to Mt. Everest. The most curious feature of the lunar mountains is their shape: most of them consist of a high circular wall sometimes as much as 100 miles in diameter, with a small cone rising in the centre, not unlike some volcanic structures on earth. The two chief theories in the field concerning the origin of these craters are that they are caused by volcanic eruptions or by the impact of a swarm of meteors. At present the available evidence rather appears to favour the second alternative.

When describing the large, dark areas on the moon the early astronomers chose names such as Ocean of Tempests, Ocean of Tranquillity, Sea of Serenity, etc., simply supposing from analogy with the earth that these areas must contain water. We

Photograph Mount Wilson Observatory

PLATE III

The northern portion of the moon at last quarter, photographed with the 100-inch reflector, and shown as it is seen in an ordinary, inverting telescope, with north pointing down. The large, flat-like crater near the bottom is Plato, about 7,000 feet high, the large, flat crater near the centre, Archimedes, just one mile high, and 60 miles in diameter. Of the two craters to the left of Archimedes, the smaller and higher is Aristillus, over 10,000 feet high. The mountain range toward the left, and above, where the sun is just setting, is called the Apennines.

know now that there is no appreciable amount of water on the moon, neither is there any atmosphere. A body as small as the moon, with a weight less than one eightieth that of the earth, cannot retain any gases on its surface; the molecules of a gas are in too violent a motion. Flying haphazardly in all directions, these molecules soon escape to the voids of space, and all that the moon can retain are a few of the lazier particles of the heavier gases and a little water vapour. The direct consequence of the absence of an atmosphere on the moon is the intense contrast it lends to the lunar landscape, making it much sharper, more beautiful, and majestic, but at the same time giving it a grim and savage, almost cruel, aspect, entirely devoid of the softness that is so typical of our terrestrial surroundings. Let us try and imagine the view of an observer who, endowed with the same senses as ourselves, could yet live in the great ring crater Copernicus.

The horizon would be much nearer, owing to the fact that the moon is so much smaller than the earth, and much more curved therefore. It might even be possible to be in the centre of one of the great ring craters, and not be able to see the walls at all. For us, who are observing from the earth, the ring craters form the most typical features of the lunar landscape. For inhabitants of the moon they might be very hard to recognize.

To an observer in the centre of Copernicus the earth would appear very nearly overhead, and,

except for a slight swaying to and fro, it would remain there. Thirteen times larger than the full moon appears to us, the earth would go through all its phases in 29 days, from "new earth," when it would shine with but a pale, bluish lustre to "full earth," forty times more brilliant than the full moon on earth. In addition, the earth would be seen to rotate on its axis, and the continents and oceans, Europe, Asia, and Africa, the Atlantic, the two Americas, and the Pacific, would be seen marching from left to right in a majestic and eternal pageant. Our Copernican could watch the sun rise and set every day upon the various parts of the earth. He could see giant storm clouds gather over the Mississippi Valley, he could discriminate between the bright yellow Sahara and the tropical forests of the Dark Continent and of South America. He would observe the straight line of the Andes, the small, compact block of the Alps, and the snow-covered Himalayas with the towering Mt. Everest.

For two weeks he would see the sun; for another two weeks he would be plunged into semi-darkness, receiving light only from the earth. Sunrise and sunset would each consume a whole day, and in the absence of an atmosphere they would be devoid of all colour. On the moon there never is a rosy dawn, never a golden sunset, nor even an azure sky. Everything is perfectly black, but exceedingly transparent, giving a spectacle so magnificent that we on earth

have nothing to compare it with. The sun, shining brilliantly in a jet-black sky, with the stars visible up to its very edge. The solar corona which astronomers on earth have to travel thousands of miles to see, and which no human can ever see for more than an hour during a lifetime, can be enjoyed on the moon for fifteen days at a time.

Though in its absence of an atmosphere the moon can have no aurora borealis, it always has the zodiacal light, a long oval of light surrounding the sun on all sides. Imagine the beauty of the Milky Way under those circumstances; its brightest patches might well look as brilliant as a white cloud in the moonlight in our sky. Thousands and probably tens of thousands more stars could be seen on the moon than on earth.

Last, but not least, comes a total eclipse of the sun, by the earth. On the moon this is not a matter of a few precious minutes or even seconds; it lasts several hours, during which time all light and heat from the sun are completely cut off. Darkness and intense cold descend upon the moon as the sun is obscured by the great black disk of the earth, fourteen times larger than the sun itself. Round the earth is a thin ring of rosy light, the earth's atmosphere, and beyond that a few streaks of light of the outer corona, and finally, on two opposite sides, the zodiacal light.

The saddest thing about the moon is its complete lack of sound; as it has no atmosphere, no sound

waves can be propagated and the moon is plunged into eternal silence. The only music one could experience on the moon would be the music of the spheres, the song sung by the grand march of the heavenly bodies as they rise and set.

Thus we see the moon through the eyes of science: dead, dry, and desolate, unapproachable and forbidding, silent and savage, but still beautiful.

Chapter V

ECLIPSES

"... a darkness which may be felt."

—EXODUS: 8, 21.

IN THE whole realm of Nature there is probably no spectacle of such awesome solemnity, nor one which leaves so unforgettable an impression, as a total eclipse of the sun. Those who have not seen a total eclipse can not truly say that they have run the whole gamut of human emotions. A total eclipse is one of those events that render one oblivious to material surroundings and thrust one beyond temporal considerations—it is something before which even the most lethargic mind becomes fervently enthusiastic.

In the full light of day the sun suddenly seems attacked by a deadly shadow, creeping on it from the west, advancing slowly but inexorably. With the gradual dimming of light, colours begin to fade, a menacing gloom takes possession of everything, and, as the darkness grows deeper and deeper, an oppressive silence sets in. The spectator becomes mentally chilled, he feels the vast and palpable pres-

ence of something cataclysmic overwhelming the world: the darkness becomes almost tangible. The sun presents a melancholy sight; reduced to the thinnest of crescents imaginable, it seems weary and ready to give up the struggle against the relentless moon. A pale opalescent glow limns the horizon, vividly silhouetting the landscape.

All eyes are intent now, watching for the great shadow of the moon approaching with terrifying speed, advancing almost as a wall, swift as thought, silent as doom. In an instant it is on us, and blackest night pervades all. It seems as if the end of all things is imminent. But out of this darkness there flashes the soft and silvery light of the incomparable corona. Its pearly and unearthly radiance, mercifully soft, yet mercilessly intense, makes us forget all things terrestrial and think only of the universe. In its ethereal glow, its aloofness, this halo of immaculate purity seems beyond all human conceptions of light and fire; while we are watching it, spellbound, it seems as if Time is not. We can but gaze at it and admire—silently, reverently, as did the ancients, who, taking an eclipse to be a manifestation of divine wrath, saw in the corona the sign manual of mercy, the symbol of victory in defeat. Though as a spectacle it is but short in duration, the memory lingers, unforgettable, etched in the mind with an accuracy, a vivid exactness, which even time can never efface. Totality is over, the light returns, and the celestial drama, symphonic

in its sweep, is ended. The earth, bathed in new splendour, appears to revive almost instantaneously; the moon's sinister spell is broken.

In former ages men's hearts trembled with fear at the thought that "the sun shall be turned into darkness." To-day a total eclipse of the sun must make its reckoning with the "unconquerable mind of man" as that mind has been strengthened by the development of scientific inquiry. The mechanism of a total eclipse was difficult to grasp for primitive man, but it appears simple to us if we only consider the relations in space of the three bodies, sun, earth, and moon.

All three are approximately spherical, the sun self-luminous, the earth and moon dark and opaque, casting long, funnel-shaped black shadows behind them where the sun's rays cannot penetrate. When, in its path around the earth, the moon becomes interposed exactly between us and the sun, the peak of its shadow falls on earth and hides the sun from our view: an eclipse of the sun takes place. When, on the other hand, the earth is between the sun and the moon, it intercepts the sunlight otherwise falling on the moon and causes the moon to be eclipsed. It is at once obvious that an eclipse of the sun can only happen at new moon, an eclipse of the moon only at full moon. That they do not occur at every new moon or full moon is due to the fact that the moon revolves about the earth in a path which deviates from that followed by the earth in its course

around the sun. For one half of the year the new moon occurs slightly south of the sun, as seen from the earth; during the other half the new moon is seen north of the sun, and only at two short intervals during the year does the new moon occur so nearly coincident in direction with the sun that an eclipse may result.

One may wonder about the fact that a body as small as the moon 2,160 miles in diameter, can hide from view a sphere as large as the sun, 864,000 miles across. The answer to this puzzle is: distance. The sun is 93,000,000 miles away, the moon no more than 240,000, with the result that, as seen from the surface of the earth, the sun and the moon *appear* to be almost exactly the same size, a circumstance which renders an eclipse just possible, though it remains a rare phenomenon. Precise calculation proves that the length of the moon's shadow varies from 228,000 to 236,000 miles, while the distance of the new moon from the surface of the earth may vary between 218,000 and 248,000 miles, thus giving rise to a multiplicity of phenomena. When the shadow exceeds in length the moon's distance from the earth, the peak of the shadow cone reaches the earth, and the eclipse is *total;* when the reverse is true, the shadow falls short and there is no place on earth where the moon appears as large as the sun, so that at best a ring of light remains around the black disk of the moon; the eclipse is *annular.*

Even in the most favourable case of a total eclipse

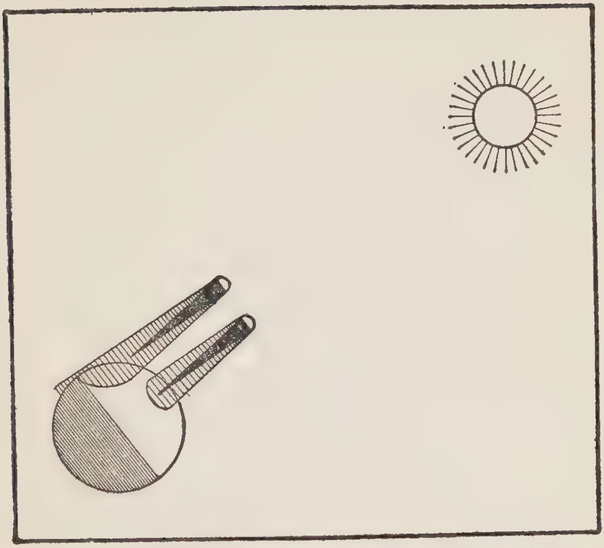


FIGURE 5.—AN ECLIPSE OF THE SUN. WHEN THE MOON IS IN THE LOWER OF THE TWO POSITIONS PICTURED, ITS LONG, BLACK SHADOW, THE "UMBRA," REACHES THE SURFACE OF THE EARTH AND PRODUCES A TOTAL ECLIPSE OF THE SUN. IF, ON ANOTHER OCCASION, THE MOON IS FARTHER AWAY FROM THE EARTH, AND IN THE UPPER POSITION, THE SHADOW FALLS SHORT, AND ONLY THE HALF SHADOW, OR "PENUMBRA," REACHES THE SURFACE OF THE EARTH: THE ECLIPSE IS PARTIAL.

the shadow has a diameter of only 167 miles, and the path of totality, the path swept out on earth by the moon's shadow, rarely exceeds 8,000 miles in length; thus, any one eclipse is total for but a small fraction of the surface of the earth. This explains why a total eclipse is such an extremely rare occurrence for any given place although, on the average, there is an eclipse of the sun more than once a year somewhere on earth. An observer outside the central line of the eclipse will not be within the sweep of the actual shadow. He will, so to speak, see sideways around the moon and still see a part of the sun's disk; for him the eclipse is *partial.*

Another consequence of the approximate equality in apparent size of the sun and moon is that an eclipse cannot last very long. In its motion in the sky the moon gains on the sun by an amount equal to its own size in about one hour; thus, on earth its shadow would sweep 2,100 miles per hour if the earth were standing still. Owing to the rotation on its axis, the earth imparts to an observer on the surface near the equator a speed of 1,040 miles per hour in the same direction as the moon's shadow is travelling; the observer, therefore, would be passed by the shadow with a speed of 1,060 miles per hour. At this rate, totality can never last longer than 7 minutes, 40 seconds at the equator, while in higher latitudes, where the speed of rotation is diminished and the speed of the shadow resultingly increased, the maximum duration is reduced; in our latitudes

totality can last but a little more than 6 minutes at maximum.

For an eclipse of the moon, the situation is entirely different; here we are dealing with the smaller moon being plunged into the shadow of the much larger earth. Because of the greater diameter of the earth, the shadow cone cast by the earth does not taper off as quickly as that of the moon; whereas the moon's shadow on the surface of the earth can never be larger than 167 miles in diameter, the shadow of the earth, where it reaches the moon, is never smaller than 5,500 miles in width, or more than two and one-half times the diameter of the moon. We have seen that the moon does not follow the same path in the sky as the sun, therefore an eclipse of the moon will not happen at every full moon, but only when the full moon occurs near the places where the two paths cross, or twice a year. When a lunar eclipse transpires, however, the moon may entirely disappear within the shadow of the earth; it may even remain obscured for one hour and forty minutes. An eclipse of the moon is a real eclipse; the moon receives no light from the sun, and, since it is not itself a luminous body, it disappears and is invisible not only from the earth, but throughout the universe. A solar eclipse, on the other hand, is merely an occultation of the sun by the moon; no actual change in the sun occurs. An observer situated outside the earth would see simply a small black dot mov-

ing rapidly over the surface of the earth. When we say that the moon disappears from view during a lunar eclipse we must not take this statement too literally; it holds true only in theory. It is true that no direct sunlight can fall on the moon at such a time, but the atmosphere of the earth bends the sun's rays into the shadow cone, with the result that the moon usually shines with a dark brown tinge and only rarely becomes entirely invisible.

As we have repeatedly remarked, the earth, in its path around the sun, and the moon, in its revolution around the earth, pursue orbits that do not lie in the same plane but make an angle of about 5 degrees. The two points, or rather, to be more exact, the directions on the celestial sphere of the two points where these two planes intersect are called the *nodes;* eclipses, as we have further seen, can take place only when full moon or new moon occur at, or near, one of these nodes. The "line of nodes," however, is not fixed in space; it rotates in such a way that every 18 years, 11 1-3 days the sun, the earth, and the moon are in almost exactly the same position relative to one another. Once an eclipse has occured, therefore, it will be repeated again 18 years, 11 1-3 days later, as was already known to the Chaldeans in prehistoric times; they named this period of repetition the *saros.* Since the saros is not equal to a whole number of days, the eclipse will not duplicate itself exactly, but be shifted westward on the surface of the earth. In

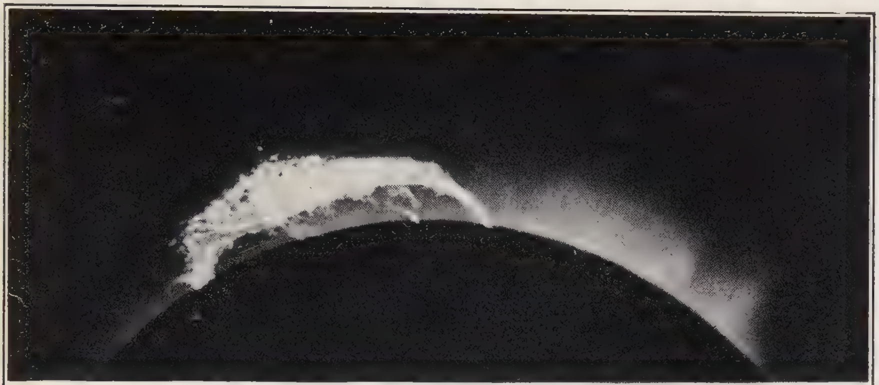
this way the total eclipse of the sun that occurred in New York on January 24, 1925, will reappear on February 4, 1943, but in Siberia, Japan, and Alaska. At its next appearance totality will be visible in France, Italy, the Balkans, and Russia, on February 15, 1961, and the original eclipse will not return to New York until 3075—after sixty-four saros periods have elapsed.

A total eclipse of the sun is visible on but a small portion of the earth's surface, and usually most of the path of totality falls over the ocean, or passes through regions of comparative inaccessibility or regions where clear weather is scarce. As a result, the number of locations with favorable observing prospects is usually very small and may require long travels. In making these long journeys to observe eclipses astronomers are not prompted chiefly by the desire for the privilege not to see the sun for a few minutes, but by the opportunity offered for making special observations which can be made only at the time of a total eclipse—such as photographic and spectroscopic observations of the corona, the chromosphere, and the "Einstein effect" (the bending of light rays near the sun's limb) which constitutes the most sensitive and most conclusive observational test of the theory of relativity. The existence of a deflection of light grazing the sun's limb in the direction and of the amount demanded by relativity was first indicated by the results of the British eclipse expedition of 1919 as discussed by

Dyson and Eddington. The question has now been settled to the satisfaction of the majority of astronomers, principally through the conclusive observation of Campbell and Trumpler at the eclipse expedition to Australia in 1922. In the future, therefore, efforts of eclipse observers will follow the path mapped out by Mitchell and others and concentrate largely on the chromosphere and the corona, concerning which our knowledge still leaves much to be desired.

When the light of the corona is examined in a spectroscope, there appears a ray of a particular yellow-green colour, which cannot be identified with light given out by any substance known on earth. Yet, the accepted ideas about the constitution of matter do not allow the existence of any more gases than we already know, and we must find the solution of the difficulty by attributing this line to one of the known gases, but one which is in a very peculiar state of electrical excitation. The second question is what causes the light of the corona: is it all reflected sunlight? and if so, what reflects it? The theory that at present seems to hold the field is that the coronal light is reflected by free electrons, particles 25 million million times smaller than an inch in diameter and carrying the smallest possible amount of electricity.

A total or partial eclipse of the moon is of much less importance, and used principally to determine the conditions of the earth's atmosphere, since the



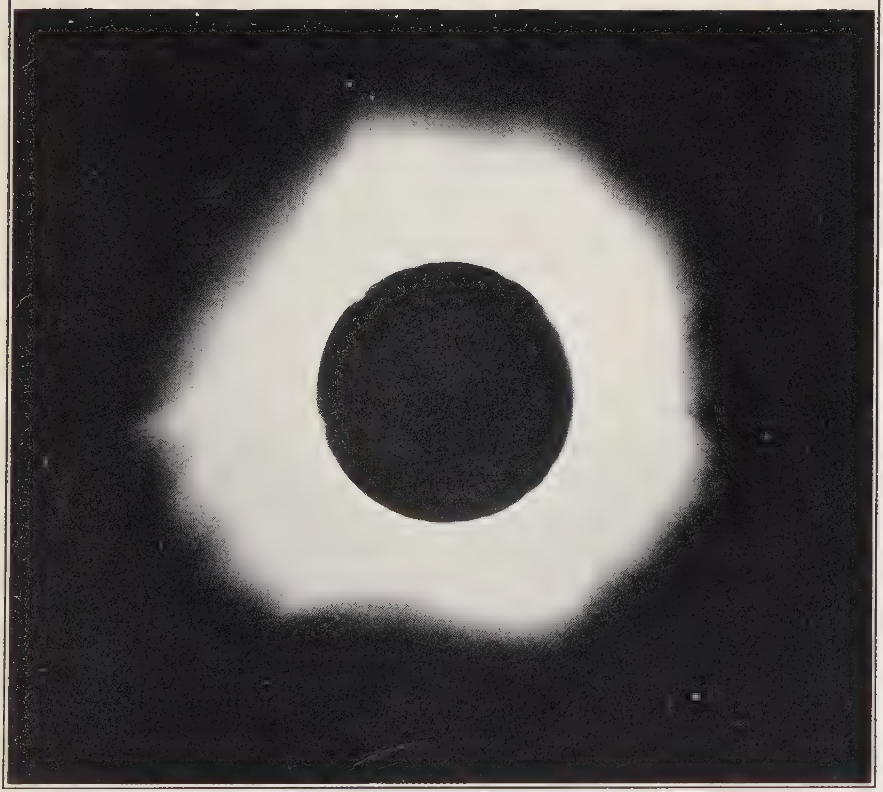


PLATE IV

Above: The great solar prominence of May 29, 1919, photographed by Crommelin, of the eclipse expedition sent out by the Royal Observatory, Greenwich, to Sobral, Brazil. The size of the earth is indicated by the small white spot at the upper left.

Below: The solar corona at the total eclipse of June 29, 1927. Photograph taken at Jokkmokk, Lapland, by the eclipse expedition of the Hamburg Observatory, under the direction of Professor Schorr.

colour and brightness of the totally eclipsed moon give a clue to the clearness or opaqueness of our atmosphere.

Within the boundaries of the United States three total eclipses of the sun have occurred so far in the Twentieth Century—on June 8, 1918, September 10, 1923, and January 24, 1925. The last-mentioned eclipse passed through a densely populated region, extending in width from New York to Providence, and was observed and enjoyed by millions of people. On April 28, 1930, the moon's shadow will barely touch the earth while it is passing through California, Nevada, Idaho, and Montana, but totality will not last more than a second and a half. A much more interesting eclipse will occur on August 31, 1932, when the line of totality runs from northern Canada, over Montreal, through Vermont, New Hampshire, Maine, and Massachusetts, the maximum duration being about one minute and forty seconds. The eclipse of May 9, 1929, in Sumatra will be total for five minutes, that of June 8, 1937, will have a duration of no less than seven minutes, almost equal to the theoretical maximum.

The prediction and calculation of solar eclipses may be done with great precision; practically their only source of error is due to uncertainties in the position of the moon. Even this source of error, however, hardly amounts to more than a second or two, and the certainty and accuracy of eclipse predictions thus stand as one of the greatest triumphs

of human intelligence. Despite his material insignificance in the universe, man is able to foretell the event with such accuracy, and describe the phenomenon in such detail, that it almost seems as if, in some way, he controlled the mechanism of the universe. A solar eclipse can no longer launch a surprise attack as in the elder time; we are waiting for it and we censure with fine impatience a second's impunctuality, as though old chaos were come again.

Before leaving the subject of eclipses we feel that we should again impress upon the reader that the sight of a total eclipse of the sun is something to look forward to. Its majesty defies prose portrayal, its beauty escapes the photographic plate. All the superlatives available in the English language are inadequate to describe even approximately the full glory of it, and though the photographic plate may record things which the human eye overlooks, and preserve details which the human mind forgets, it cannot reveal the magnificence of a total eclipse. Only a direct view of the eclipse itself makes us realize so vividly the utter insignificance of man, the futility of all things material; only the eclipse experience itself can make us reach that crucial point in philosophical reflection where we feel we can rise above things terrestrial and become one with the conception of space and time.

Chapter VI

THE TERRESTRIAL AND MINOR PLANETS

"And what are the planets? Drops of a mixture of mind, a little mire, and plenty of moisture."
—FRANCE.

NOW that we have come to the description of the other members of the sun's family, it is natural that we should begin at the centre and travel from the sun outward. The first planet we meet, then, is Mercury, not only the nearest to the sun, but the smallest, lightest, and swiftest of all planets. The path of Mercury around the sun is also the most elongated of all, the planet's distance changing from 28,000,000 miles in *perihelion,* the point nearest the sun, to 43,000,000 miles in *aphelion,* the point farthest away from the sun. It requires 88 days for the planet to complete this course, traveling at an average speed of 30 miles per second. Since the path of Mercury around the sun lies entirely inside that of the earth, we can never see the planet recede from the sun by more than a given angle, which, in the case of Mercury, varies from 18 to 28 degrees,

depending upon the position of the planet in its ellipse. Consequently, Mercury is visible only a short while after sunset, or before sunrise, and is one of the most difficult objects to observe with the naked eye. Many astronomers indeed, among them the celebrated Copernicus, have never seen it. Like the moon, Mercury is a dark body, shining only by reflected sunlight; like the moon, therefore, it will show phases depending upon its position relative to the sun and the earth. With the phases, its distance from the earth varies considerably, from 136,000,000 miles when the planet is on the other side, presenting a fully illuminated disk, to 50,000,000 miles when it is between us and the sun. The first phenomenon is called *superior conjunction,* the second, when it is "new" Mercury, *inferior conjunction.* Occasionally it may happen that Mercury passes so exactly between us and the sun, that we see it projected against the sun's disk, crossing it slowly as a small, black spot as large as a silver dollar half a mile distant. These *transits* of Mercury are rather rare occurrences, happening about twelve times a century. They are, however, of great astronomical importance, since they furnish an opportunity for determining Mercury's position with great precision. From observations made at such times the French astronomer Leverrier, and later Newcomb, calculated that the elliptic orbit of Mercury was turning around in space, and moreover, turning around faster than could be explained

by the attraction of the other planets. The speed of this rotation was such that in three million years the orbit made *one* more turn than it should, an amount so great that, for years, it has presented the most serious discrepancy in celestial mechanics.

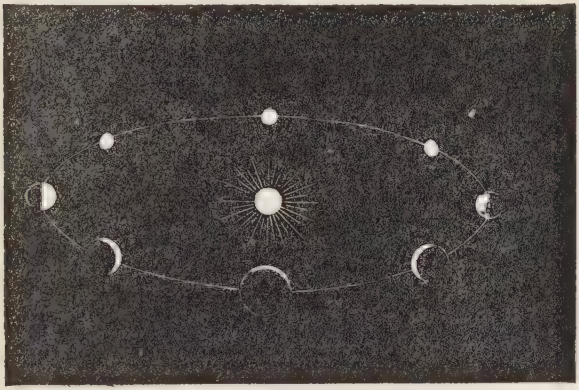


FIGURE 6.—THE MOTION OF AN INNER PLANET AROUND THE SUN, SHOWING THE CHANGES IN PHASE AS WELL AS IN DIAMETER, DEPENDENT UPON THE RELATIVE POSITION OF THE PLANET WITH RESPECT TO THE SUN AND THE EARTH.

The explanation was not given until Einstein came with his theory of relativity, and the fact that this "advance of the perihelion" of Mercury had already been observed was a strong and significant factor in the argument for the acceptance of relativity.

In concluding, a few more figures may be added: Mercury has a diameter of 3,100 miles, and weighs

about one thirtieth part of the earth. The density is 0.7 that of the earth, or almost four times that of water.

Between Mercury and the earth circles Venus, of all planets the one most comparable to the earth. Like Mercury, Venus can never recede further than a certain distance from the sun, but, since Venus is nearer the earth, and much larger in size than Mercury, it is a much more conspicuous object in the sky. When Venus is to the left of and following the sun, it may set as many as three or four hours later. It is then seen as our brilliant "evening star," far surpassing all other objects in the sky in brightness. At these times of greatest apparent distance from the sun, Venus may easily be seen in the daytime, if one knows where to look for it. When the planet is to the right of the sun, it precedes and rises before the sun: it is then our "morning star." The ancients did not notice for a long time that the morning star and the evening star were the same object. The Greeks even had a different name for each: Phosphorus for the morning, Hesperus for the evening star.

On the scale of the astronomer who expresses brightness on a logarithmic scale where smaller and negative numbers indicate greater brightness, Venus may become as bright as −4.3, more than one hundred times as bright as the average star of the first magnitude. On the same scale Mercury never

reaches greater brightness than −1.2, not quite nine times a first magnitude star.

In its path around the sun Venus travels in an almost perfect circle with a radius of 67,000,000 miles; the time it takes for one complete revolution is 225 days, moving on the average with a speed of 22 miles per second. Its diameter is 7,700 miles, or almost as large as that of the earth, but owing to the great variation in distance from the earth, ranging from 26,000,000 miles at inferior conjunction to 160,000,000 miles at superior conjunction, the apparent size of the planet varies from 64 seconds of arc to only 10, or from 29 times smaller than the full moon to 180 times smaller. The occasions upon which Venus passes so nearly between us and the sun that we see it cross the sun's disk are very rare indeed, the last event of this kind having taken place in 1882, while the next one will not happen until 2004.

The mass of Venus, determined by the effect it has upon other planets, is found to be 81 per cent. of that of the earth. Since its volume is 92 per cent. of the earth, it follows that the density is 88 per cent. of that of the earth, almost five times that of water. It has been shown by observations made near the time of inferior conjunction that Venus has an atmosphere which can be observed to be more than a mile high, but which contains practically no oxygen. However, it is entirely probable that what we observe is really the outer part of the

atmosphere, and that the whole planet is surrounded by a thick layer of clouds.

Venus and Mercury are the only planets known inside the orbit of the earth; they are sometimes called the inferior planets. Neither has any satellites so far as we know. It has been suggested from time to time that there is still another planet nearer the sun than Mercury. The most careful observations made during an eclipse of the sun have thus far failed to reveal a trace of it, and it appears that, if such a body exists at all, it can be no more than thirty miles in diameter. Beyond this we have no information concerning the existence of this *intramercurial* planet; faith, however, has outrun knowledge on this occasion, and the planetary infant has been formally christened Vulcan.

Seen from Venus, the earth is the brightest object in the firmament; with the moon, it forms a beautiful double star. At the time of its closest approach to Venus the earth would outshine an average first magnitude star more than 300 times, while our moon, revolving around the earth at a distance of one degree (twice the diameter of the full moon as seen from the earth), is 40 times fainter, but still one of the brightest lights in the sky.

From Venus we travel farther out, pass the orbit of the earth, and come to Mars, the ruddy planet symbolic of the war god of the ancients and even now the subject of many a quarrel between scientists. Of all the celestial bodies visible to man,

Mars occupies the most outstanding position. Fiery red, almost menacing in its savage lustre, at times the brightest star in the sky, Mars was from time immemorial regarded as the symbol of destruction, the personification of the god of war. It was made the scapegoat of all human crimes and follies, and to its pernicious influence was ascribed all disasters that befell humankind. To-day Mars occupies the centre of the discussion of the habitability of other worlds. It is the subject on which writers with a fertile imagination have lavished too much attention, and consequently it has become the chief subject of disagreement between the layman and the professional astronomer, one of the permanent liabilities of the profession in the public eye.

Before we venture into the precarious question of habitability, let us first examine the facts in the case: Mars revolves around the sun in an elliptic orbit, changing its distance to the sun from 128,000,000 to 154,000,000 miles. As a result of this eccentric orbit of Mars, the planet changes its distance of closest approach to the earth considerably. It may come as close to us as 35,000,000 miles, while at other times it does not come within 62,000,000 miles. Its brightness may vary, as a consequence, from -2.8 or considerably brighter than the brightest star in the sky, to -1.1, not quite as bright as Sirius, dependent on whether the nearest approach, or opposition, to the earth is "favorable" or not. It takes the planet 687 days to complete

one revolution around the sun, but 780 days to take up the same position again relative to both earth and sun. This is the time that elapses between two *oppositions,* the positions such that the planet is opposite the sun, as seen from the earth.

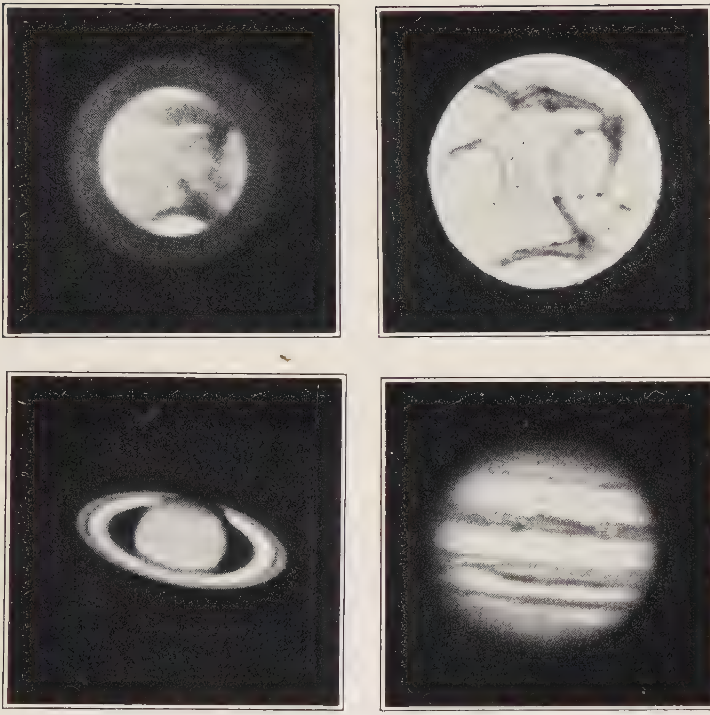
Mars is a small planet, only 4,215 miles in diameter, a little more than half that of the earth, and only one seventh of the earth in bulk. Observations of the satellites give for its mass the value one tenth of the earth, thus making its density 0.72 and gravity at the surface 0.38; that is to say, a man weighing 160 pounds on earth would weigh no more than 60 pounds on Mars. From observations of markings on the surface of Mars it has been possible to determine with great precision the time it takes the planet to rotate on its axis; from data gathered during the past two hundred years this time has been calculated as 24 hours, 37 minutes, 22.58 seconds, with an uncertainty of no more than a few hundredth parts of a second. The axis of rotation on Mars makes approximately the same angle with the plane of its orbit as on the earth. The seasons, then, must be very nearly the same as ours. An observer on Mars, however, would not see the heavens rotate around our pole star, but around the star Delta Cephei, a faint star situated about midway between Cassiopeia and Deneb, the brightest star in the Swan.

The planet possesses two satellites, discovered by Asaph Hall at the Naval Observatory, Wash-

ington, in 1877; the outer one, which revolves at a distance of 15,000 miles in 30 hours, is called Deimos (Terror); the inner one, which is no more than 6,000 miles from the centre of Mars, or less than 4,000 miles from the surface, revolves in 7 hours, 39 minutes and is named Phobos (Fear). They were so named after the legendary companions of Mars, or Ares, the god of war. These two moons are among the smallest and most curious bodies known in the whole solar system. The inner one, Phobos, revolves around Mars from west to east in less than one third of the time the planet itself rotates on its axis from west to east. In our own case the earth rotates much faster from west to east than the moon revolves around us; consequently, the moon lags but little behind the stars and rises in the east. On Mars, however, Phobos overtakes the rotation of the planet, rises in the west, and sets in the east. Deimos, much slower in its revolution around Mars, behaves more normally and does rise in the east, but it takes its time about it and remains above the horizon for almost three days. Compared to the planets and the other satellites of the solar system, these two moons are but small fragments of dust. Phobos is probably no more than ten miles in diameter, Deimos even less, probably about five; even so, they are both so close to the surface of the planet that, seen from there, Phobos would be only three times smaller in diameter than the full moon and twenty five times

fainter, while Deimos would be of the same appearance as Venus seen from the earth.

Since Mars can come very close to us the topography of its surface is better known than that of any other object in the sky except the moon. A small telescope will show only the *polar cap,* a brilliantly white spot near one of the extremities of the axis of rotation, and without doubt due to sunlight reflected from the ice and snow that gathers there during the Martian winter. This polar cap is seen to diminish in size, due to melting of the ice and snow as Martian spring and summer advance, as may easily be seen on the excellent photograph of Mars taken by E. C. Slipher at Lowell and by Wright at Lick. Recent work done by Coblentz and Lampland at the Lowell Observatory and by Pettit and Nicholson at the Mt. Wilson Observatory has shown that the temperature in these regions is about 100 degrees below zero, Fahrenheit, so long as the snow is present, but that after it has melted the temperature may rise to 50 degrees above zero and become equal to the midday temperature at the Martian equator. The night temperature, even at the equator, must be very low, however, and might well be below zero the year round; at sunrise and sunset it may be just above zero. Spectroscopic investigations carried out at the Lick and Mt. Wilson Observatories have indicated the presence of a little water vapor and oxygen, in amount about 5 per cent. and 15 per cent.



Photographs by E. C. Slipher. Lowell Observatory

PLATE V

The telescopic appearance of three of the brighter planets. In the upper part of the illustration a drawing and corresponding photograph of Mars are compared. In the photograph (on the right) the polar caps are well shown, while the "canals" are less distinct than in the drawing. In the lower left, Saturn and its rings are photographed in one of the positions most favorable for observation. In the lower right, on the disk of Jupiter, are the equatorial belts, and, near the right margin, the Bay of the Great Red Spot.

respectively of that normally in the atmosphere of the earth. On the whole there is probably no more than 10 or 20 per cent. of the atmosphere we have on earth.

When more powerful telescopes are used, not only the polar caps but a wealth of other details are revealed on the surface of Mars, among them the famous "canals." These were first discovered by Schiaparelli at Milan, in 1877, and named *canali* because they appeared as straight lines of a dark colour up to fifty miles wide, several hundreds of miles long, and traversing the Martian continents in all directions. When later Lowell, at Flagstaff, Arizona, saw the whole Martian surface covered with a maze of these canals it became almost inevitable that they should come to be interpreted as artificial—the work of intelligent beings. Human beings? Possibly, though no one has as yet dared to go that far. At any rate, it has brought up the question of the possibility of life on Mars, and this has led to the problem of what "life" is, and has brought with it a disagreement between the astronomer and the public. When the astronomer talks of life on Mars he would include all possible kinds; the layman, on the other hand, would mean principally human life. The latter is not concerned with fungi or bacteria, or even plants. Bacteria, so small that they run through the finest filters in our laboratories, may be of interest here if they cause cancer: they are of no

interest whatever across a chasm of 50,000,000 miles.

Percival Lowell did go so far as to suppose a race of intelligent beings on Mars, capable of such engineering feats as the construction of canals 2,000 miles long. The underlying reason was obvious: since Mars is a dying planet, its inhabitants found it becoming so difficult to live there that they had to turn, as a last resort, to herculean methods for irrigating the arid equatorial deserts, the only regions warm enough to live in, and irrigate them by means of the snow and ice stored up at the poles. Lowell even went to the extent of calculating that a pumping system necessary for such planetary circulation of water required an expenditure of energy 4,000 times the power of Niagara.

Other astronomers have taken opposite views. The existence of canals in such numbers as indicated by Lowell is denied, and the fact that the canals are seen to cross the seas is taken as proof that they cannot contain water. W. H. Pickering, one of the most profound students of the subject, has come to the conclusion that it is not the canals themselves we see, but the much wider strips of vegetation on their banks. The whole question is far from settled as yet, and it will take many years before observations are in sufficient agreement to enable us to discuss the question of life on Mars properly. All that we can say now is that when reviewing the different prerequisites a planet must

fulfill in order to allow life comparable to life on earth, we find that the conditions are just met on Mars, but no more than that. If, therefore, life does exist on Mars, it must be under severe conditions and can hardly be compared to the easy ways of our planet.

With Mars we have finished the description of the terrestrial planets; outside these we find the four major planets, Jupiter, Saturn, Uranus, and Neptune. The gap between the orbits of Mars and Jupiter, however, is disproportionately large and destroys the symmetry of the system, as older astronomers, even those of Kepler's time, had remarked long before Uranus and Neptune were known. When Bode's "law" of the increase in the mean distance of the planets from the sun was formulated, and when shortly afterward Uranus was discovered and found to conform to Bode's law, the lacuna between Mars and Jupiter became more and more evident. Astronomers were now firmly convinced that there must be still another, as yet unknown, planet in this region, and societies were formed whose aim it was to search for the missing link. It was the good fortune of Piazzi at Palermo, Sicily, to discover an object which later proved to be the long-sought-for planet; using his right of naming it, he chose the name Ceres after the ancient goddess of Sicily. After having first noticed it on the first day of the preceding century (January 1, 1801,) as a star-like object in the con-

stellation Taurus, Piazzi followed its course for a time, but was taken ill shortly afterward; before he recovered the planet had disappeared in the evening twilight. The difficulty then arose to calculate the path of the new object from these observations, in order that it might be rediscovered in future. It was in this way that Gauss was furnished with the inspiration which led to his invention of the method of deriving the orbit of a celestial body from three observations.

A year later a second planet, Pallas, was discovered by Olbers; a third one, Juno, by Harding in 1804, and a fourth, Vesta, again by Olbers, in 1807. Then followed thirty-eight years of fruitless search, but from 1845 on hardly a year passed in which there were not one or more new objects of this type discovered, some years yielding as rich a crop as one hundred new discoveries. During the past few decades the search has been greatly intensified by the introduction of photography, and the total number of these bodies has grown so enormously that to date already more than one thousand have had reliable orbits determined, while almost as many others have been discovered, but observed insufficiently to permit a calculation of their path. Instead of merely filling a vacancy in the solar system, the small planets have become almost a nuisance through their large numbers: once hailed as the "missing link," they are now maligned as the "vermin of the sky."

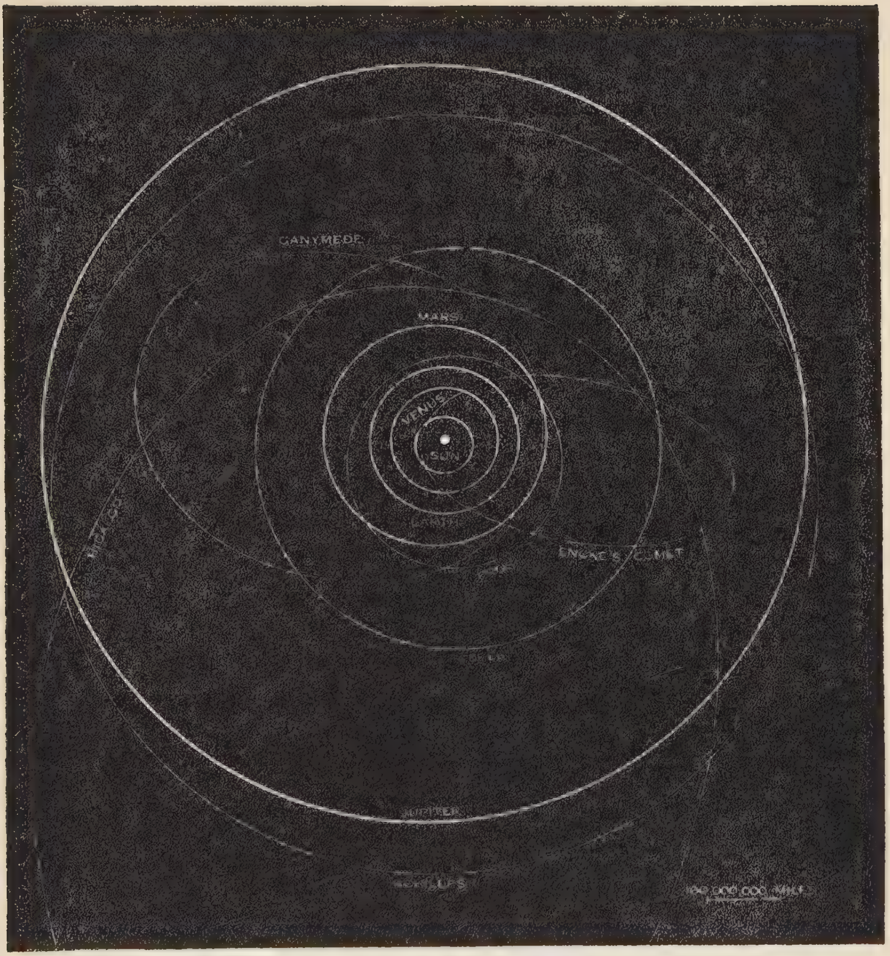


FIGURE 7.—THE INNER PART OF THE SOLAR SYSTEM. THE ORBITS OF MERCURY (NOT LABELLED), VENUS, THE EARTH, MARS, AND JUPITER ARE INDICATED BY HEAVY CIRCLES; THOSE OF FOUR ASTEROIDS AND OF ENCKE'S COMET BY THINNER ELLIPSES.

The large number of small planets (or asteroids, as they are unfortunately and infelicitously called) now known more than fill the gap between the orbits of Mars and Jupiter; they fill it to overflowing. Their system of orbits is so complicated, however, that, if each orbit were represented by a thin ring of steel wire, one could lift them all, by moving only one. In their paths around the sun the asteroids follow ellipses as do the planets, but their orbits are much more elongated, much more *eccentric,* than those of the planets. Contrary to the behaviour of the planets, the asteroids do not, as a rule, follow the plane of the ecliptic very closely, but may make large angles with it. In mean distance from the sun they range from 1.46 astronomical units for Eros to 5.71 for Hidalgo; since the mean distances of Mars and Jupiter are 1.52, and 5.20 respectively, we see that the asteroids have indeed filled out the gap to overflowing; they have not, however, filled it uniformly. They seem to avoid certain values for the mean distance from the sun, as first noted by Kirkwood, and mathematical analysis has shown that this is not due to chance, but a direct consequence of the perturbations exerted by Jupiter, the giant planet of the solar system. The influence of Jupiter on an asteroid at any one time is very small indeed, but allow Jupiter enough time and its disturbing attraction, recurring with deadly precision every twelve years, will drown out all asteroids that are moving in synchronism. Synchro-

nous action is one of the most powerful destructive agents of nature; no swing can withstand the effect of periodic blows recurring at intervals equal to the

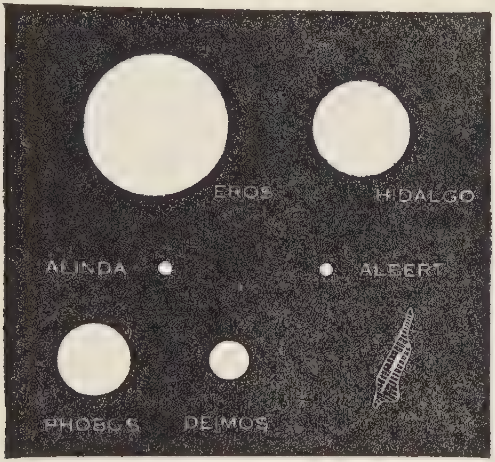


FIGURE 8.—SOME OF THE PYGMIES OF THE SOLAR SYSTEM. TWO OF THE SMALLEST KNOWN ASTEROIDS, THE TWO EXCEPTIONAL ASTEROIDS EROS AND HIDALGO, WHOSE ORBITS ARE SHOWN IN FIGURE 7, AND THE TWO SATELLITES OF MARS ARE HERE COMPARED IN SIZE WITH MANHATTAN ISLAND. IT IS SEEN THAT ALBERT AND ALINDA ARE NOT MUCH LARGER THAN CENTRAL PARK.

time of swinging. We have already seen how the earth, through the recurrent tides which it raised on the moon, has subjected that body to its will and made it rotate on its axis in the same period in

which it revolves around the earth. Indeed, though the mills of the gods grind slowly, yet they grind exceeding small!

The asteroids are all small bodies, the largest known one, Ceres, being only 480 miles in diameter, while many of the smaller ones are undoubtedly no more than a few miles in size, no larger than Manhattan Island. Their mass, compared to that of the earth, must be very small, one ten-thousandth at most. Ceres and Pallas, the two largest ones, are estimated to weigh about this much, but the combined mass of all asteroids, known and unknown, is probably not much over one thousandth part of that of the earth.

When asteroids were first discovered, the theory was proposed that they perhaps formed the remains of one single planet which had exploded, leaving its fragments to pursue their own paths around the sun, each being subject to a different perturbative influence of Jupiter. Mathematical analysis has shown, however, that Jupiter never could have altered the orbits of such a collection of asteroids into the present heterogeneous mixture. Although, for this reason, the theory that *all* asteroids had a common origin has to be abandoned, it may still be true for certain smaller aggregations. A striking tendency to gregariousness has been noticed among these small celestial bodies; Hirayama in Japan has identified several "asteroid

families," some containing as many as forty members.

Of all asteroids known at present, Eros, number 433 in order of discovery, is undoubtedly the most interesting. Eros describes a very elongated ellipse, which lies for the larger part *inside* the orbit of Mars. It may approach the earth within 13,000,000 miles, closer than any other planet; it is then of great value for determining the exact dimensions of the solar system by direct triangulation. As we have seen before, the solar system can be very easily mapped on a relative scale, the chief difficulty lying in the determination of the exact scale value. It is in this instance that Eros is useful, because of its short distance from the earth. Other remarkable asteroids are Albert (No. 719) and Ganymede (No. 1036), both of which may come inside the orbit of Mars, and Hidalgo (No. 944), whose orbit is an ellipse almost touching the orbit of Mars, on the one hand, and that of Saturn on the other. Lastly, there is the group of *Trojan planets,* composed of Achilles (588), Patroclus (617), Hector (624), Nestor (659), Priamus (884), and Agamemnon (911), all of which revolve around the sun at the same distance as Jupiter. Thus, it can be proved mathematically that they must always be near a point which forms an equilateral triangle with the sun and Jupiter. This is actually the case, Patroclus and Priamus following Jupiter, and the other four preceding.

Perhaps the strangest asteroid of all is that discovered recently in Japan and provisionally named Tokio. A preliminary orbit determined for it indicates that it moves in an ellipse far more elongated than those of many comets and reaching as far as Uranus. The path of Ceres, as an example of a typical asteroid, and those of Eros, Ganymede, Achilles, Hidalgo, and Tokio, as exceptional asteroids, are portrayed in figures 7 and 9.

Chapter VII

THE MAJOR PLANETS

"If they are inhabited, what worlds of misery; if they are not, what a waste of space."

—CARLYLE.

THERE is no greater contrast in the solar system than the transition from the asteroids, that host of small and innocuous planetary fragments, to Jupiter, the giant of the planets, larger and heavier than all the rest put together. Although never attaining as great splendor as Venus, and even occasionally surpassed in lustre by Mars, Jupiter is yet, through its much slower motion, the most conspicuous object in our night skies. Its steady, pale yellow light, coupled with its slow, majestic progression along the firmament, have earned for it its name, that of the god among gods.

At its equator Jupiter has a diameter of 88,640 miles, slightly more than eleven times that of the earth, but its polar diameter, owing to the very rapid rotation of the planet, and the consequent flattening, is considerably less, only 82,880 miles. This causes the disk to appear very flattened, so

much so in fact that this flattening can be easily seen through a small telescope. The weight of Jupiter is the one most accurately computed in the whole solar system; it has been determined from the planet's influence on the motion of asteroids and from its own satellite, and has been found to be 313 times that of the earth, or 1,047 times less than that of the sun. Since the volume of Jupiter is 1,312 times larger than that of the earth, its mean density is less than one fourth of ours, or 1.34 times that of water.

Jupiter travels around the sun in an ellipse which does not greatly deviate from a circle. The circle has a mean radius of 483,000,000 miles, and it takes the planet almost twelve years to complete one turn, while its average speed is 8 miles per second. While it revolves about the sun, Jupiter spins on its own axis in 9 hours, 55 minutes. A "year" on Jupiter, therefore, has no less than 10,000 Jovian days. Since the axis of rotation is almost perpendicular to the plane of the orbit, there are no seasons on Jupiter, only perpetual spring.

Even a small telescope will show the principal features of Jupiter's surface, several wide, diffusely outlined belts, usually identified as clouds. Meteorologically speaking, Jupiter is quite different from the four terrestrial planets, as may be observed even in an ordinary telescope. A magnifying power of fifty makes Jupiter's disk appear as large as the moon to the naked eye; under such magnifi-

cation one can see very clearly that the surface is crossed by several wide, diffusely outlined belts, more or less parallel to the planet's equator. A larger telescope, and a higher magnification will reveal more detail, especially a beautiful contrast in colours. It will then also be noticed that this detail on the surface is continually changing in position, due to the planet's rotation, and in character, due, no doubt, to real changes in Jupiter's atmosphere. It was formerly supposed that, since Jupiter has such a dense atmosphere, it must also be considerably warmer than the earth, at the surface at least, and perhaps hot enough to emit some light of its own. Recent accurate measures made by Lampland at the Lowell Observatory indicate that the light we receive from Jupiter is entirely reflected sunlight, and that the temperature at the surface cannot be far from 200 below zero, Fahrenheit. For this reason, it has been suggested that the planet has a central core of dense material, not unlike the rocks on our surface, but is surrounded by a thick layer of ice, and the whole enveloped in a dense atmosphere.

As we might have anticipated from its great mass, Jupiter is not a solitary planet, but has a number of attendant satellites: nine are known at present. The four brightest were found by Galileo as soon as he turned his telescope on Jupiter on January 17, 1610, and they may be seen with any telescope, even with the help of a good field glass.

Under exceptional conditions some of them may be seen with the naked eye. Although they have been given names, they are usually referred to by number, in order of their distance from Jupiter. The masses of these satellites are determined from their mutual attractions and the disturbance of their orbits, and are found to be not very different from that of our moon. Since the first two are of the same size as our moon, they are probably composed of similar material, resembling the rocks on the surface of the earth; the third and fourth are almost four times the bulk of the moon and may, according to an interesting suggestion made by Jeffreys, consist largely of ice or solid carbon dioxide.

All four satellites revolve around their primary in circles which lie very nearly in the plane of the ecliptic, and they are thus seen sideways from the earth. Consequently, we see them move only from right to left, and they always appear to be very nearly in a line which passes through Jupiter. As seen from Jupiter's surface, where sunlight is only one twenty-seventh as intense as on earth, the first satellite would appear five times fainter than the moon, and the other three still fainter. The inner three of Jupiter's moons are so close to the surface of the giant planet that once during every revolution they pass behind it and into the great shadow cone; they are eclipsed. The fourth satellite is far enough away so it may escape eclipse occasionally. Conversely, during every revolution around Jupi-

ter, the satellites pass in front of it and cast their shadows, visible from the earth as small black spots moving rapidly over the planet's surface. These two types of phenomena, eclipses of the satellites and transits across the disk, form a spectacle most interesting to watch from the earth. When Jupiter is in opposition to the sun—that is, when the earth is between it and the sun—the planet's distance from us is considerably less than when the planet is in conjunction, or on the other side of, behind, the sun, so to speak. Eclipses of satellites, which in reality occur at regular and stated intervals, will appear to be retarded in the latter case and advanced in the former, simply because the rays of light which are carrying the message of the event have a longer way to travel in the second case. Arguing from this principle, Olaf Roemer, a Danish astronomer of the Seventeenth Century, first determined the velocity of light from the known distance of Jupiter to the earth and from the observed advance and delay of the eclipses.

For almost three hundred years the four Galilean satellites remained the only ones known—until, in 1892, Barnard at the Lick Observatory discovered a fifth one very close to the surface of the planet and performing one whole revolution in less than twelve hours. This fifth satellite appears as a star of the thirteenth magnitude, one million times fainter than Jupiter, and it is without doubt one of the most difficult objects to observe. The sixth and

seventh satellite were discovered photographically by Perrine at the Lick Observatory, the eighth by Melotte at Greenwich, and the ninth by Nicholson, again at Lick. They are all exceedingly faint objects, observable only with the most powerful photographic telescopes, although the sixth has occasionally been seen visually.

A curious feature of the last two moons is that their motion around Jupiter is opposite to the usual direction of motion in the solar system. To an observer situated far north of the plane of the ecliptic, the earth and all other planets would be seen revolving around the sun in a direction contrary to that of the hands of a clock; the same would be the case for the motion of the moon around the earth, the moons of Mars, and the innermost seven satellites of Jupiter; they would all appear to move counter-clockwise. The outer two, however, would move clockwise. As a result, it has often been the subject of speculation whether Jupiter has come by these two of its moons honestly, or whether, perhaps, they are not ancient asteroids captured by Jupiter. On the whole, mathematical astronomers are now inclined to believe that the nine known satellites are all permanent members of Jupiter's family, although the possibility that Jupiter has lost satellites in the past or will capture others in the future has not been entirely ruled out.

With Saturn, the planet next to Jupiter, we approach the ancient frontier of the solar system; the

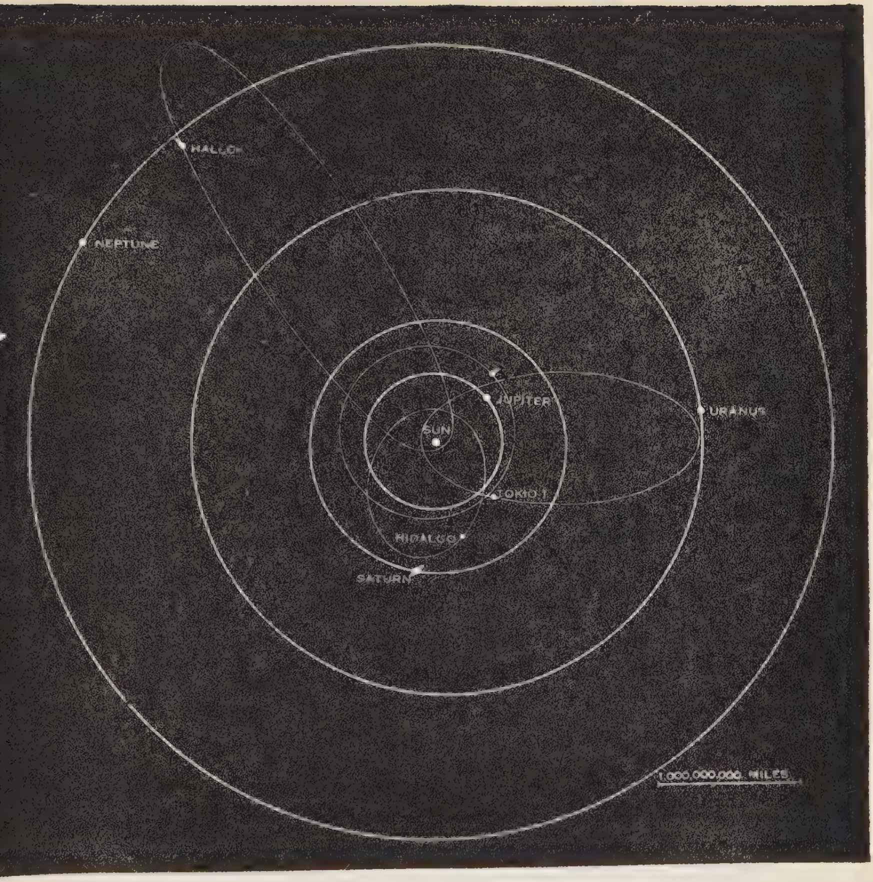


FIGURE 9.—THE OUTER PARTS OF THE SOLAR SYSTEM. THE ORBITS OF THE FOUR MAJOR PLANETS, JUPITER, SATURN, URANUS, AND NEPTUNE, ARE HERE INDICATED BY HEAVY LINES. HIDALGO REPRESENTS THE OUTERMOST ASTEROID, HALLEY'S COMET THE FARTHEREST OUTPOST AMONG THE COMETS THAT ARE KNOWN WITH CERTAINTY. OF THE MORE RECENT DISCOVERIES, THE ORBITS OF COMET SCHWASSMANN-WACHMANN (NOT LABELED), AND OF THE ASTEROID TOKIO 1 ARE GIVEN.

distance of 886,000,000 miles that separates Saturn from the sun is the remotest to which the unaided human eye had penetrated in the planetary system. On account of its greater distance from the sun, Saturn is the slowest of all planets readily visible to the naked eye; in addition, it is also the faintest, though still as bright as a star of the first magnitude. The peculiar, "livid" hue of its light together with its sluggishness of motion made this planet the symbol of immutable fate to the ancients. By the astrologers of old, Saturn was regarded as the chief "malefic," the principal inciter of disaster that made all those unlucky ones born under its spell suffer forever after: through Saturn spoke the "voice of destiny."

It takes Saturn about 29.5 years to complete its orbit around the sun, an orbit which is more elliptical than that of Jupiter, the distance from the sun varying between 840,000,000 and 940,000,000 miles. The planet itself, too, is very far from a perfect sphere, and the flattening at the poles may be seen through any small telescope. The equatorial diameter is 74,000 miles, the polar diameter only 66,000, which makes the bulk of the planet 734 times larger than that of the earth. Its mass, which is determined with great accuracy from its satellites as well as from its influence on Jupiter, is not proportionately greater, but only 95 times that of the earth. It follows that the mean density is only one eighth that of our planet, or only seven

tenths that of water: if we could only find an ocean large enough, Saturn would float. From the fact that Saturn turns on its axis in a little more than ten hours, mathematicians have deduced that most of the surface layers must be gaseous, and that much of its total weight is concentrated in a rather small core at the centre. These surface layers are at a temperature slightly lower than that of Jupiter, about 240 degrees below zero.

In size, weight, and brightness Saturn must bow to the superiority of Jupiter. As a sight in the telescope, however, Saturn far surpasses all other objects in the solar system; it is unique in our experience with nature in that it is surrounded by a ring. When Galileo turned his first telescope on Saturn, he noticed two "supplements," one on each side of the planet, and he thought the object to be triple. His telescope was not quite good enough to show the ring, and it was not until Huygens observed it in 1655 that the true form of the ring became known. Later, the French astronomer Cassini found that the ring really consists of two concentric rings, separated by a thin gap which appears as a black line in the telescope. Still later, Bond of Harvard and Dawes in England found a third ring, rather hazy in appearance, which forms the innermost boundary; it is called the "crêpe ring." This extreme inner edge of the ring is only 7,000 miles from the planet's equator and 11,000 miles in width; the outer portions are 16,000 and

10,000 miles wide respectively, while the black gap is no more than 3,000 miles wide. The ring forms an angle of about 28 degrees with the ecliptic, and during Saturn's revolution around the sun the ring remains parallel to itself. Consequently, it must happen twice during their course around the sun (that is to say twice during Saturn's year, or once every fifteen years) that the rings are pointed directly at us and we see them "edge-on." This is really identical with saying that we do not see the rings at all for they are so thin that even with the largest telescopes one may scan in vain for them at such times. From this it has been estimated that they cannot be much more than 10 miles thick.

Observations with the spectroscope have proved that the rings do not constitute one solid body, but that they are composed of a great swarm of minute particles—meteors, so to speak—each revolving separately around Saturn. In a way then, the ring becomes analogous to the belt of asteroids in the solar system, and indeed there are many points of resemblance. We have seen before how there are certain gaps in the mean distances of the asteroids from the sun, owing to the impossibility of maintaining an asteroid in motion where it moves in synchronism with the powerful disturbing force of Jupiter. Here, in Saturn's ring, we have a miniature edition of the same story; the asteroids are replaced by the particles of the ring, and the rôle of the wicked uncle is played by the satellites nearest

to Saturn. The black division discovered by Cassini is thus explained by the action of Mimas, the nearest satellite.

This brings us to the satellites, for, in addition to its rings, the distant world of Saturn is accompanied by no less than ten moons. Nine, named in order of their distance from Saturn: Mimas, Enceladus, Tethys, Dione, Rhea, Titan, Hyperion, Iapetus, and Phoebe, are known with certainty, while the tenth one, Themis, was seen but a few times and lost again; it cannot now be identified. Titan, the first to be discovered, is the largest of them all, slightly exceeding our moon in size, while the others range from 150 to 1,000 miles in diameter. Phoebe, the outermost of all, revolves backward around the planet, as do the eighth and ninth satellites of Jupiter; the other eight moons of Saturn behave normally. The masses of the satellites were determined by the influence of their mutual attraction and the resulting perturbations of their orbits; they are by far the smallest masses that have ever been determined in this way. Titan is almost twice as heavy as our moon, Mimas less than one thousandth part of our moon, while the others range in between.

The solar system of the ancients, consisting of the sun, the earth, the moon, and the five planets visible to the naked eye, Mercury, Venus, Mars, Jupiter, and Saturn, had been enlarged and extended by the discovery of several satellites, but

the invention and application of the telescope had not added any new planet; no new independent body had joined the ranks. When, on March 13, 1781, William Herschel discovered a new object which proved to be a planet revolving about the sun in an orbit lying entirely outside that of Saturn, the discovery created great excitement. The iron-bound limits of the solar system had been broken, new vistas had been opened, and free rein could be given to the imagination concerning the completion of the planetary system.

Herschel named his star Georgium Sidus, after George III, then king of England, but fortunately for the impersonal character of science, the mythological name Uranus, the father of Saturn, prevailed.

After Herschel's discovery it was found that the same object had been observed many times before but that it had always been mistaken for a star. It has even been said that the inhabitants of some island in the South Seas knew of it, not as a star, but as a planet wandering through the heavens. This is just possible, for Uranus, under favourable conditions, is well visible to the naked eye if one knows where to look for it.

The mean distance of Uranus from the sun is 19 astronomical units or 1,782,000,000 miles; the actual distance, however, fluctuates between 1,700,000,000 and 1,870,000,000, owing to the ellipticity of the orbit. Travelling at the rate of only 4¼

miles a second, Uranus needs 84 years to complete one turn about the sun. The other facts known about Uranus are that its diameter is about 32,000 miles, its volume 64 times that of the earth, and its mass 15 times greater than that of our planet; it rotates on an axis in about 11 hours, and has four satellites. In order of their distance from Uranus, these are named Ariel, Umbriel, Titania, and Oberon. They are all exceedingly faint objects and therefore very small, probably no more than a few hundred miles in size.

When Uranus had been observed some fifty years it became evident that the planet did not follow the "true" course mapped out for it by mathematical calculation. During this interval the planet often strayed away from its computed position by as much as 20 seconds of arc; that is, by as much as the distance across a dime when seen from a distance of 400 feet. In 1845 these deviations had accumulated to almost 2 minutes of arc, one fifteenth of the moon's diameter, an "intolerable quantity." Such a state of affairs could not be endured, the mysterious source of these discrepancies must be discovered; and almost simultaneously two astronomers, Leverrier in France and Adams in England, undertook to do it. Independently, and almost simultaneously, they came to the same conclusion: there was an unknown planet, revolving far beyond Uranus, but of sufficient mass to pull Uranus out of its path. Both computers made the

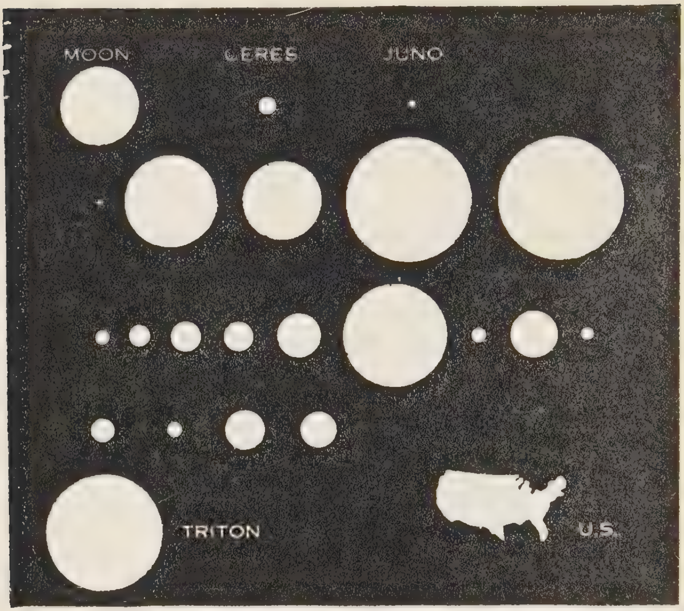


FIGURE 10.—THE MOONS OF THE SOLAR SYSTEM. IN ADDITION TO OUR MOON AND THE ASTEROIDS CERES AND JUNO, THE FIGURE SHOWS, IN THE SECOND ROW, THE RELATIVE SIZES OF THE SIX LARGEST SATELLITES OF JUPITER, ARRANGED IN ORDER OF DISTANCE FROM THE PLANET. THE REMAINING THREE SATELLITES ARE TOO SMALL TO BE SHOWN ON THIS SCALE. THE THIRD AND FOURTH ROW PICTURE THE PROBABLE SIZES OF THE SATELLITES OF SATURN AND URANUS RESPECTIVELY, ALSO ARRANGED IN ORDER OF THEIR DISTANCE FROM THE PLANET. AT THE BOTTOM TRITON, NEPTUNE'S ONLY SATELLITE, IS PORTRAYED, AND A MAP OF THE UNITED STATES ON THE SAME SCALE IS ADDED FOR COMPARISON.

same prediction concerning the position of the new planet, but Adams had the bad luck of finding no responsive audience, while Leverrier was astute enough to write to the Berlin Observatory, asking them to verify his discovery. But we are not doing Leverrier justice. He did not write and ask for *verification;* he laconically told Galle, an astronomer in the Berlin Observatory, that "if he looked in a certain position in the sky, he would find the new planet." So convinced was Leverrier of the correctness of his calculations that he never gave himself the trouble of looking for the new planet; in fact, he died in 1877, on the exact thirty-first anniversary of the discovery, without ever having seen it. He had reason indeed to trust his calculations: when Galle, after receiving Le Verrier's letter, pointed his telescope to the sky, he immediately found the new planet, within *one degree* of the predicted position. The name Neptune was unanimously adopted for this remotest of planets.

The discovery of Neptune, from mathematical calculation alone, is one of the most eloquent witnesses of the power of the human mind. We may well say that it represents the crowning achievement of abstract reasoning in any science. The presence of a new planet had been *felt,* owing to some apparently trifling discrepancies in the motion of an object 1,780,000,000 miles distant; the new planet had been *seen* with the spiritual eye of the astronomer by means of his equations, his formulæ,

and his tables of logarithms. Verification then remained merely as one of the commonplace details of everyday life.

Neptune revolves about the sun in an almost circular orbit, at a distance of 30 astronomical units, or 2,800,000,000 miles. It is the only one of the planets for which Bode's law of planetary distances breaks down, since this law would predict a distance of 39 astronomical units. Neptune's speed is only a little more than 3 miles per second, and it therefore needs 165 years to complete one revolution around the sun. The planet's diameter is 31,000 miles, its mass 17 times that of the earth; it appears to us as a star of the eighth magnitude, invisible to the naked eye, but, if one knows where to find it, visible in an opera glass. Neptune has one satellite, sometimes called Triton, an exceedingly faint object, which revolves around Neptune at a distance of 220,000 miles, and which is probably very similar to our moon.

With the modern increase in accuracy of observations, slight irregularities have been noticed in the motions of Uranus and Neptune, which, again, cannot be explained by the action of the sun and the known planets. Again the conclusion has been reached that there may be another planet beyond Neptune, which may be responsible for these deviations. Unfortunately, the discrepancies in the present case are so small that no very definite conclusions can as yet be reached concerning such a

trans-Neptunian planet, except that there cannot be a planet as large as Neptune within twice the distance of Uranus, or one as large as Jupiter within 2½ times the distance of Neptune. W. H. Pickering has announced as a not unreasonable prediction that the new planet, planet O, revolves about the sun in a very elliptic orbit at about the same mean distance as Neptune, that it cannot be much heavier than about half the weight of the earth, and that it should appear to us approximately as a star of the twelfth magnitude.

With Neptune we have reached the boundary of the planetary system. Before we pass on to a description of the more vagrant members of the sun's family, the comets, let us view in retrospect what we have passed through. If we should try to make a model of the solar system on the scale of one to one billion, we should have to represent the sun by a sphere four feet in diameter. At a distance of 70 yards we should find Mercury, one fifth of an inch in diameter; at 120 and 170 yards respectively, Venus and the earth, both half an inch in diameter; at 250 yards a smaller globe, a quarter of an inch in size, representing Mars. Then would follow a host of sand-grains, as the asteroids, and at half a mile from the central sun we should find Jupiter, four inches in diameter. One mile away would reach Saturn, almost as large as Jupiter, and at distances of two and three miles respectively, Uranus and Neptune, each two inches in size. By

the time we arrived at these outposts the inner parts would have disappeared from view: our human eyes, if transferred to Neptune, would be unable to see one single planet with ease. Jupiter and Saturn might be observed close to the sun, and Venus and the earth perhaps during a total eclipse, while the other three would remain invisible. The sun would appear 900 times smaller in area and 900 times feebler in light than from the earth. The sun's heat would be inadequate to warm us; it could not raise the temperature above 360 degrees below zero. Here, at last, at the barrier of the sun's empire, the perpetual cold of empty space has vanquished the life-giving heat of the sun.

Chapter VIII

COMETS AND METEORS

"Wan, dishevelled, slow, fatigued, glides before us the wandering comet in the night of its aphelion."

—FLAMMARION.

COMETS have long held the unenviable position of scapegoats in astronomy; they have for ages past been blamed for all the misfortunes befalling the human race, in man's simple desire to shift the responsibility for things terrestrial to forces and things out of his reach, in the sky. Comets, as weird apparitions, rare and sudden in their occurrence, offer only too good a target for such accusations. The sight of a great comet blazing forth in the blackness of the nocturnal sky is an imposing sight, indeed, and not likely to be easily forgotten. Hence the numerous allusions to comets throughout the literature, sometimes as descriptions of painstaking minuteness, sometimes in language of grotesque extravagance. Especially the ancient Chinese records reveal some past masters in this noble art.

Our word comet is derived from the Greek *kometes,* "the long-haired," a most obvious description. Contrary to our present views, however, the ancients considered comets to be vapors in the atmosphere, or exhalations from the earth. Among the minor disasters that were supposed to accompany these missionaries of evil, were famine, pestilence, and wars. Now all these associations have disappeared, and only the name stands, though even this proves hardly deserved. Great comets, with long tails like those that terrified the ancients, are still seen as frequently as ever, but in addition the modern observing methods have revealed the existence of large numbers of faint comets entirely devoid of tails. Strange to say, however, the great modern telescopes have not played a prominent part in the discovery of comets; that is largely due to amateurs, observing with comparatively small telescopes, and to the use of photographic cameras. The reason is that our giant telescopes have such a high magnifying power that only a very small portion of the sky can be examined at one time, and the chances for discovery then are much less favorable than for amateurs who sweep the sky with small telescopes with large fields of vision. "Comet hunting" is quite a sport, but the rewards it yields are small: one comet a year is considered a good average for the assiduous observer, although sometimes a lucky catch is made, as by the late Rev. Joel

Metcalf, who once found three new comets within forty-eight hours.

When a comet has been discovered the news must be communicated to the world at once, and in astronomy all roads lead, not to Rome, but to Harvard and Copenhagen. A code telegram announcing the discovery is immediately dispatched to these two centres, whence the news is relayed to all other observatories. Now the large telescopes come into play, accurate observations of the new object are secured, and these, too, are at once cabled to Harvard and to Copenhagen, and again relayed. As soon as three accurate observations have been obtained the computers set to work, and within twenty-four hours they produce the orbit of the comet, its path around the sun, which will enable them to predict its future course among the stars. Very often such an orbit is only a first approximation, and further observations are required to clear up doubtful points. Some comets disappear again so quickly that there is no chance for further refinement, and the first preliminary orbit is the best we can do. In that case it is generally impossible to say whether the comet is a permanent member of the solar system, if it will return, and how soon. When we do get sufficient observations to calculate the path of a comet in more detail, we almost invariably find that it describes an ellipse, a closed curve, and thus it will come back again after a number of years. It is only very rarely, and then

always with suspicions and reservations, that the computations lead us to suppose that the comet travels along a parabola, or a hyperbola, an open curve, in which case it will recede again to infinity, never to return. On the whole it looks as if practically all comets are describing closed paths around the sun, that they all come back to the sun at their appointed times. Sometimes these paths are very long ellipses, ovals, with the sun near one of the ends of the curve. In those cases it may take the comet thousands and perhaps millions of years to complete one turn; at other times the ellipse found is very short, and the comet may be expected back in a few years. And thus it seems as if really the vast majority of the comets are permanent members of the sun's family; we have no longer the right to consider them as interlopers from space, as messengers from some far-distant part of the universe that have merely come to pay the sun homage, but have not come to stay. This does not mean, however, that comets are as regular members of the solar system as the planets. Far from it; comets are very erratic in their behaviour. From the fact that they traverse the solar system in long ellipses, reaching beyond the orbit of Neptune in some cases, it follows that sometimes these wanderers of the wasteland may come very close to one of the larger planets, and be deflected from their course. Their entire orbit may be changed, as happened, e. g., to the comet Brooks. Delving into its history by

means of calculations, it was found that this object used to travel around the sun once in thirty years, but that it imprudently came very close to Jupiter in 1886. The attraction of this giant among the planets was so powerful that it shortened the comet's path: thereafter it went around the sun in seven years. It was first discovered by Brooks in 1889, but split into four pieces at that time, and when it came around again in 1896, in 1903, and in 1911 it had lost so much of its brilliance that it could only be seen in the largest telescopes. In 1918 it was not found, and astronomers feared that its career might come to a sudden and tragic end, when computations showed that in 1921 it would again approach Jupiter very closely. Nothing much seems to have happened at that occasion, however, since the comet returned in 1925, on time but looking very much the worse for wear.

In contrast to this one, some other comets behave almost as normally as the planets themselves. Encke's comet, first seen in 1786 and since then observed every three and one-half years, is as regular in its appearance and disappearance as may be desired. A remarkable comet was discovered by Schwassmann and Wachmann in 1927, for computations of its path showed that it remains always outside the orbit of Jupiter, and always inside that of Saturn. If it were not such an exceedingly hazy and tenuous object we should probably call it an asteroid; now we call it a comet, though really there

is not much to choose between these two names. In volume this comet must have been larger than Jupiter, yet it undoubtedly weighed many times less than the moon.

The most famous comet of all times is unquestionably Halley's, so named after Edmund Halley, the contemporary and close friend of Newton. When in 1682 a brilliant comet appeared in the sky, Halley and Newton set out to calculate its path, following the rules and principles just enunciated by Newton under his law of universal attraction. Halley then applied himself to do the same for notable comets that had appeared in the past, and found to his amazement that the orbit of the new comet was practically identical with those of the comets of 1531, and 1607. Halley quickly grasped the significance of this: it must have been the same comet, which therefore must have a period of about 75 years, and he immediately ventured to predict its next return for 1758.

Nowadays, when it is possible to observe a comet for three nights and to have its complete path around the sun less than twenty-four hours later, it is hard to realize what an epoch was marked in astronomy by Halley's prediction. It was the first real test of Newton's great law of universal attraction, the first time a scientific forecast had been made for the remote future and with full confidence of its ultimate realization. And yet little attention was paid to it in the beginning. Halley died in

1742, seventeen years before his comet could reappear to make his fame. As the year 1758 drew nearer, astronomers revived Halley's work and proceeded to look into the matter a little more closely. With the great progress celestial mechanics had made in the meantime, it was possible for the French astronomers Clairaut and Lalande to take into account the influence of Jupiter and Saturn. They came to the conclusion that the comet would not return until the beginning of 1759, and predicted that it would reach its closest distance from the sun, its *perihelion,* toward the middle of April, 1759, with an uncertainty of a month. And, indeed, the comet was first picked up on Christmas Eve, 1758, by a farmer in Saxony, and it did pass through perihelion on March 12, 1759. It appeared next in 1835-36, and from observations made at this epoch the French astronomer Pontecoulant predicted its subsequent return for May, 1910. In 1908 Cowell and Crommelin in England began their new computations, using the best possible data for the solar system and taking into account the perturbations not only of Jupiter and Saturn but of Uranus and Neptune as well. For more than seventy years the comet had been invisible even in the most powerful telescopes, but the eye of the calculations had nevertheless followed it closely; had, so to speak, seen it turn in 1873 at the extreme end of its orbit, more than three billion miles from the earth and beyond even the orbit of

Neptune, the farthest outpost of the solar system. The calculations had followed the comet so closely through all its encounters with the various planets that when it was ultimately discovered by Wolf, on September 11, 1909, it was only seven minutes of arc from its predicted place. Less than one fourth of the moon's diameter, and less than a quarter of an inch on the original photographic plate!

By looking into old records and searching Chinese chronicles, Crommelin and Cowell were able to trace back, with only one exception, every return of Halley's comet since the year 240 B.C. Notable appearances were those of 11 B.C. (which by some is identified with the star of Bethlehem), when it "foretold the death of Agrippa in Rome," of 1066, when it was regarded as a portent for the Norman Conquest, and of 1456, when it was immortalized in France on the famous Bayeux tapestry.

At its last appearance, in April and May, 1910, Halley's comet showed a tail 120 degrees long; in the tropics the tail would rise several hours before the head of the comet became visible. In linear measure the tail must have been at least 20,000,000 miles long. On May 19, 1910, this enormous comet, tail and all, passed between us and the sun, at a distance from us of only 15 million miles, and in such a way that the tail pointed practically straight at us. Seen from the earth, the comet would appear projected on the sun's disk for more than an hour. For all this time astronomers searched and searched in

vain; not a trace of the comet was visible, not the slightest obscuration of the sun's light did the comet effect. In spite of its great light-reflecting power, the comet and its enormous tail appeared perfectly transparent.

Another comet, that of 1680, must have passed very close to the sun itself, and cannot have been more than 600,000 miles from the sun's surface. The great comet of 1843 did better than that even: it approached the sun to within 80,000 miles of its surface, at which point it received more than two million times as much light and heat from the sun as we do at noon on a summer day. Yet it got away again by virtue of its great speed, several hundred miles per second, which enabled it to run more than halfway around the sun in less than two hours. Even so, when we know that solar explosions may reach a height of 200,000 miles above the sun's surface, and that the corona, the sun's outer atmosphere, extends well over a million miles beyond the sun's surface, it seems incredible that the comet got away unscathed. More than that: it got away in style, too, supporting a tail of more than 300,000,000 miles long. If this tail had been a rigid fixture of the comet, the other extremity of the tail would have swept over a distance of no less than 800,000,000 miles during the two hours that the comet itself turned halfway round the sun. This would correspond to a speed of more than 100,000 miles per second, and even if such great speeds were

possible, particles of the comet's tail travelling at this rate would soon become dissociated from the comet; they would pursue their own course in space, and pay very little attention, even to the sun. We are thus forced to the conclusion that the tail does not really belong to the comet; it is already lost, and will be left behind in space.

The comet of 1843 stands by no means alone in this peculiar behaviour; the comets of 1668, 1680, 1702, 1882 I (discovered during a total eclipse of the sun), of 1882 II, the greatest spectacle of the Nineteenth Century, and that of 1887 all came exceedingly close to the sun, and what is more they all described similar paths round the sun. Although it is perfectly certain that these comets are not identical, it seems probable that they are all remnants of one and the same really magnificent comet, which once came a little too close to the sun and broke in pieces, leaving each piece to travel along a path of its own liking.

Other comets, though not able to produce such a prodigiously long tail as that of 1843, are still remarkable for the large number of tails they had. The great comet of 1744, according to a fairly authentic account, had six enormous tails, Dunlop's comet of 1825 had five; but the record is held by Borelly's comet of 1903, a fairly small object, but still able to grow nine tails, as is shown on photographs taken at Greenwich. Morehouse's comet of 1908 was even more freakish. On September

PLATE VI

Above: Path of a comet around the sun, showing the lengthening of the tail as it approaches the sun.

Below: Two photographs of Comet Morehouse, taken at the Yerkes Observatory, three and one-half hours apart, showing the motion of the tail in this interval. (Since, as is evident from close inspection of the two photographs, the comet moves among the stars, and the telescope had to be pointed directly at the comet throughout each exposure, the stars have formed short "trails" on the picture.)

29th of that year it appeared perfectly normal, on September 30th the tail began to explode and disrupt, little by little, and on the following day it had entirely disappeared. A few days later, however, the comet, not unlike a lizard, had grown a new tail and it underwent several more complete metamorphoses in less than a day.

Biela's comet of 1845 neatly divided into two parts which, for a while, kept on travelling together, and at the next return of the comet, in 1852, were only a million miles apart. The two fragments disappeared from view in September, 1852, and they have never been seen again. They were expected back in 1859, 1865, and 1872, and especially at the last-mentioned epoch the comet should have been very favorably located for observation. Nothing was seen, except a brilliant display of meteors in 1872, and again in 1885 and 1892. There seems no other conclusion left but that Beila's comet has disintegrated, worn out, and vanished, and we have had to write it off our books. Other comets have exhibited similar testimony of decay and it is generally believed that the majority of comets are only temporary phenomena which, like moths at a candle, burn their wings when they get too close to the sun and ultimately disintegrate and vanish. Some comets seem to have hardy constitutions, on the other hand. There is the case of Encke's, which has occasionally returned with new vigour; it has even been accused of having been to a restau-

rant. As yet, we have been unable to detect either the location or the bill of fare of this all-night restaurant that apparently operates in darkness.

All this gradually brings us to the question: What are comets? Why do they, and they alone of all the bodies in the solar system, have tails? We have already seen that in all probability they are permanent members of the solar system, *débris,* so to speak, left behind when the other star, which caused the catastrophic birth of the planets, left the solar neighbourhood. Being so very light and tenuous in substance, they may have strayed away very far before they ultimately bowed to the stronger will of the sun's attraction. This may explain why we find comets revolving about the sun in all possible directions, whereas the planets are practically confined to the same plane. That comets are very light we cannot doubt; even the gigantic comet of 1843, which, tail and all, contained more than 1,000,000,000,000,000,000,000 cubic miles of luminous material, failed utterly and completely to make any impression on the planets. Its total mass was so small that not the slightest deflection could be observed in the motion of the planets. When we say small, we mean astronomically small, of course; small compared with the earth or the moon—expressed in tons it may still be a redoubtable number. Donati's comet of 1858 has been estimated to weigh certainly less than one third of one million

million million tons, or less than one twenty-thousandth part of the earth.

When it comes to explaining what the tail of a comet is, we must keep in mind that a tail is really only a temporary fixture: all the material particles in the tail, which we see because they reflect sunlight, are already lost to the comet. Through the work of the Russian astronomer Bredichin we know that the tail consists of large numbers of exceedingly small particles which, under the action of the strong sunlight, or the light pressure as it is called, are streaming away from the comet. For ordinary matter this pressure of light is insignificant when compared with the attraction exerted by the sun. When things get smaller and smaller, the pressure of light becomes relatively larger, and for particles only one twenty thousandth of an inch in diameter, light pressure and gravitation balance; for still smaller particles light pressure wins. And indeed, as observations have shown, the small particles of matter driven out of the comet's head by the action of the sun's light and constantly accelerated by this same force are acquiring more and more speed as they get farther out; ultimately they may reach speeds of sixty miles a second.

As for the physical constitution of comets, we believe at present that the central part of the head may contain large quantities of iron, but the spectroscope has proved that the gases immediately surrounding the head are largely made up of carbon

monoxide and cyanogen, with some sodium vapor added.

In recent years our discoveries of new comets (i. e., not counting predicted returns of already known periodic comets) have averaged about five a year. Now it is perfectly obvious from the haphazard way in which these discoveries are made that we are not getting more than a fraction (and a small fraction at that) of the total number of comets each year, not even of those that are within reach of our telescopes. So that, conservatively speaking, we may put the number of new comets appearing each year at twenty-five. We do not know how long we could go on finding this many new comets each year before exhausting the whole stock, but we do know that comets, on the whole, wear out pretty rapidly, astronomically speaking; furthermore, we know that many of them have excessively long periods of revolution, counted in thousands and possibly in millions of years. Since we have no reason to suppose that the present time is peculiarly plentiful in comets, and since we know further that the solar system must have existed for a very long time, probably millions of millions of years, it follows that the total number of comets in the solar system must be enormous. There must be billions, possibly trillions of them, and no matter how small and light they may be individually, their total mass may be considerable. It may very well

be comparable to or even exceed the mass of the earth.

If we consider comets as the rather numerous but vagrant and independable members of our solar system, we can go a step farther, and take a look at *meteors* or "shooting stars," which obviously surpass comets in all these characteristics. Meteors constitute our daily visitors from the great beyond; they form our only direct contact with the material world outside the earth, and as such are of the greatest importance. Meteors are the only things that can give us reliable information concerning the emptiness of space, and yet we know very little about them. We know that they are generally small particles of matter that come through our atmosphere with terrific speeds, heat up through the friction they encounter, and when they are hot enough to emit light appear to us as "shooting stars." Usually they are very small, sometimes no larger than a grain of sand, and their glory lasts but a short time; in a few seconds they are burned out, but during these few seconds they are raised to a temperature of 6,000 degrees centigrade, and give off energy at the rate of 4,000 horsepower. Occasionally, meteors are so huge that even their racing through the whole of our dense atmosphere does not suffice to burn them up, and they strike the ground with a terrific roar, often accompanied by a hail of smaller particles. The largest meteor thus far found was discovered by Peary in Green-

land, and is now on exhibition in the American Museum of Natural History, in New York; it weighs no less than thirty-six and one-half tons. There are hopes that we may find a bigger one yet in the near future, for scientists are now pretty well convinced that "Coon Butte," a great crater in Arizona near Cañon Diablo, was formed by the fall of a huge meteorite. It is a crater in the middle of a desert 4,000 feet in diameter, with walls rising 150 feet above the surrounding plain and descending precipitously to the floor, 600 feet below. There are no signs of volcanic action in the neighborhood, and all around the crater, even imbedded in the walls of it, there have been picked up fragments of meteorites, or stones containing a mixture of iron and nickel. We have learned through chemical analysis that many meteors consist of a mixture of very pure iron with some nickel or cobalt, and such a combination of metals is rarely found elsewhere.

Since meteors form our only means of direct communication with the stars, their chemical composition is of special interest; it furnishes us with the only tangible information concerning the chemical make-up of the stars. It is fascinating to think that when we take up a piece of a meteor, we may be holding in our hand a piece of matter belonging to a star which has exploded millions of millions of years ago. How can we be so certain that meteors come from the stars? you may ask. Why

cannot they too, like comets, all belong to our solar system? For this belief we have conclusive evidence in the velocities of the meteors. If they really were permanent attendants of the sun, none of them could have speeds exceeding 26 miles per second. Even if a meteor fell into the sun from an infinite distance, it could not attain a speed higher than 26 miles a second by the time it crossed the earth's path around the sun. Direct observations of meteors have revealed that at least some of them have speeds as high as 45 miles per second, putting them well outside the class of solar meteors.

Among the slower meteors, those that travel with speeds less than 26 miles per second, and are therefore permanent members of the solar system, we find many great aggregations apparently traveling the same path around the sun, and some of these can be identified with the orbits of comets. We have already seen that Biela's comet has disappeared and given way to a swarm of meteors; likewise, we know of meteors traveling the same path as Halley's comet. During the summer of 1927, when Pons-Winnecke's comet was unusually close to the earth, Yamamoto at Mukden, Manchuria, saw and photographed an exceedingly bright meteor, many times brighter than the full moon, which was shown by the calculated path to have been connected with that comet. A swarm of meteors travelling round the sun in such a manner that they meet the earth annually in August, thus

causing a brilliant display, a "shower" of meteoric fireworks, are probably the remains of some prehistoric comet.

While the chemical analysis of meteors furnishes a clue to the composition of the stars, the abundance of meteors in space gives an indication of the emptiness of space. That is to say, if we knew how many meteors of each different size strike the earth every day, we should be able to tell how much matter there really is in empty space, a thing all astronomers are very anxious to find out. Unfortunately, our knowledge in this instance is deplorably incomplete, and all we can say is that probably not less than ten million meteors strike the earth every day. As an interesting by-product of this, it follows that the earth is getting heavier all the time, and must therefore gradually slow down in its rotation. Since the added mass of the meteors would also increase the sun's attraction, it would tend to make the earth's orbit smaller, and thus shorten the year. The day would be getting longer and the year shorter, but, as Young has calculated, this change would not amount to more than one one-thousandth of a second in a million years.

We have now reached the end of the sun's domain. We have passed beyond the orbit of Neptune, the furthest outpost among the regular members of the sun's family, we have passed beyond even the most far-flung of the comets and streams of meteors, we have surveyed all that shines by the

reflected glory of the sun. All this will fade into insignificance as we continue farther. As we go beyond, into the vast stretches of interstellar space, and look back, we see only the sun. Only the sun remains, and even the sun is now reduced to the level of merely one among countless millions of other stars.

Chapter IX

THE NATURE OF THE STARS

"'The time has come,' the walrus said,
'To talk of many things:
Of shoes and ships and sealing wax,
Of cabbages and kings.'"

—CARROLL.

IN THE solitude and silence of the nocturnal sky the stars give the only manifestation of a something existing throughout the unfathomable depths of space; were it not for them, the whole realm of space would be in the grip of perpetual darkness. Small wonder indeed that the ancients saw the heavens as the celestial stage upon which the gods performed and wielded their magic, using stars and planets as pawns to dictate their caprices to humanity. Out of the mists of antiquity there come to us whispers from the book of Job, from Homer, concerning the symbolism by which the sky of prehistoric times was identified—a symbolism laden with portents boding good or ill for human kind. It was thus that the constellations originated, as also the star names, and with them the first description of the heavens. Astronomy of to-day has, of

necessity, out-grown this nomenclature of yesterday; no longer do we refer to the stars by fanciful names such as "the star on the left claw of the Scorpion" or "the red star on the eyelid of the Bull," but rather designate them by letters and numbers, an identification much less ambiguous and less subject to the individual imagination. Thus Sirius, the brightest star in the sky, is astronomically called Alpha Canis Majoris, indicating that it is the brightest star in the constellation of the Greater Dog; the Pole Star, for similar reasons, is called Alpha Ursæ Minoris, or in this special case, Polaris. For fainter stars the designation of Argelander is employed, in whose system the sky is divided into 180 narrow zones one degree wide running parallel to the equator, and each star given a number in the zone to which it belongs.

Within the past forty years a number of observatories have coöperated to map and catalogue, by means of photographic plates, the precise positions of three to four million stars, distributed over the whole sky. At present about three quarters of this work has been completed. The number of very faint stars is so vast that it is of little use to devise elaborate systems of identification; usually only a rough position in the sky is given, and, for a few stars that merit special attention, small charts of the region immediately surrounding them are prepared and filed away. In recent years photography has completely supplanted the older method of mapping

the sky by plotting the positions of all stars observed on a chart, not only because the new method is much less laborious, but principally because a direct photograph constitutes a lasting record of the sky, often invaluable for later investigation. Through the great foresight of Pickering, the Harvard Observatory was one of the earliest in the field of astronomical photography. Since 1887 it has continuously and systematically photographed the entire sky from its two stations in Cambridge and Arequipa, Peru.[1] The photographic library thus accumulated numbers to date almost 400,000 plates, and contains such a wealth of information that we may well say that its value will not be exhausted as long as the photographic film remains intact.

A first arrangement of the stars immediately suggests itself when we observe them differing considerably in brightness. The Greeks already distinguished several classes among them; they named the brightest stars in the sky, stars of the *first magnitude,* and stars just visible to the naked eye, stars of the *sixth magnitude,* the others being graded in between. When telescopes revealed increasingly large numbers of still fainter stars, these had to be fitted into the system by assigning them to the seventh magnitude, etc., greater numbers indicating smaller brightness. Lack of uniformity between estimates made by different observers naturally led

[1] This southern branch of the Harvard Observatory was moved to Bloemfontein, South Africa, in 1927.

to the establishment of a rigorous mathematical system of grading stellar brightness. In this system the faintest stars visible to the naked eye are still called stars of the sixth magnitude, but stars of the fifth magnitude are defined as those 2.512 times brighter than the former, stars of the fourth magnitude as 2.512 times brighter again. This number 2.512 has been chosen for the reason that now five magnitudes difference in brightness corresponds exactly to a ratio of 100 times in actual light, thus making a first-magnitude star exactly 100 times brighter than one of the sixth. Insistence on precision subsequently resulted in the use of decimals, so that we now speak of a star of magnitude 5.52; in addition, it has been found that there are a few stars in the sky brighter than the first magnitude, such as Vega, Arcturus, and others. Not to upset the mathematical basis of magnitude scales, these had to be labelled stars of zero magnitude, and the two stars still brighter, Canopus and Sirius, were designated as of the magnitudes minus one and minus two respectively. Exact measurement has shown that the light we receive from Sirius is equal to that of a candle at a distance of 200 yards, while an average first-magnitude star corresponds to a candle at 600 yards. Continuing in the direction of greater brightness, it has been found that the light of the full moon corresponds to a stellar magnitude of −12, that of the sun to −27. Principally owing to the efforts of Pickering at Harvard, we are now

in possession of accurately measured magnitudes of all stars brighter than the sixth magnitude, and of tens of thousands of stars fainter than that limit.

Telescopes with a light-gathering power much greater than that of the human eye will naturally show stars much fainter than the sixth magnitude. An opera glass of 1-inch aperture shows stars of the ninth magnitude, or 15 times fainter than those just visible to the naked eye; the 36-inch telescope of the Lick Observatory shows stars down to the seventeenth magnitude, the 100-inch at Mount Wilson stars of the nineteenth magnitude. Long-exposure photographs made on sensitive plates will reveal still fainter stars, and it seems safe to conclude that with the 100-inch telescope at Mount Wilson we could photograph, if we wished, all stars brighter than the twenty-first magnitude; that is, all stars not more than 1,000,000 times fainter than the limit of visibility of the naked eye.

Stars of this extreme faintness, however, exist in such multitudes that it seems at present not worth the effort to record them all. The chief thing we want to know about them, namely, their approximate total number, may well be derived by other, and simpler, though indirect means. Statistics here come to the aid of the astronomer, and the problem is solved in much the same way as the medical man solves his public health problems. When the latter wants to determine the influence of a certain disease, he is usually unable to gather reliable informa-

tion for the whole country and has to be content with obtaining them for certain communities where he knows he is getting the whole truth and nothing but the truth. Similarly with the astronomer in his attempts to count the stars in the sky. He is unable to count them all individually, and therefore takes photographs of a large number of restricted areas distributed all over the sky and counts the number of stars per square inch on these plates. Knowing how large an area of the sky is represented by a square inch on his plates, he then takes the average of his counts, multiplies by the whole area of the sky, and the result will give him the desired number. For the brighter stars, of course, this procedure need not be used, since they can be counted directly; only the fainter stars require statistical methods.

The whole sky contains twenty stars which are of the first magnitude or brighter, some sixty stars brighter than the second magnitude, five thousand stars brighter than the sixth, and more than one million stars brighter than the twelfth magnitude. the total number of stars observable with the 100-inch telescope, stars brighter than the twenty-first magnitude, is probably not less than one-thousand million. In spite of the rapid increase in numbers, the fainter stars do not contribute much to the total light of the stars in the sky, and this total amount of light is known with far greater precision than is the number of stars. Newcomb first made an esti-

mate of the total brightness of the sky; more recent measures by Van Rhijn indicate that total starlight is equal to about 1200 stars of the first magnitude, or 120 stars as bright as Sirius, and less than 1 per cent. of the light of the full moon.

Apart from their difference in brightness, the stars may be seen with the naked eye to differ in colour. Some stars appear white, others yellow, while a few even merit the adjective red. Vega and Sirius are examples of the white class, Capella and Arcturus of the yellow, Betelgeuse and Antares of the red group. Since the stars are self-luminous bodies, a difference in colour immediately suggests a difference in temperature, and brings to the mind what happens when we heat up a bar of iron. At a comparatively low degree of heat the iron will appear red hot, at a higher temperature it seems pale yellow, while in the Bessemer converter or in the electric furnace it appears intensely luminous and white. The same holds for the stars, as indeed the spectroscope has shown that the white stars are hotter than the yellow or red stars. When the light of a star, concentrated by means of a telescope, is passed through a prism and spread out into a colored band of light, a spectrum, it is found that such a star-spectrum, like that of the sun, is not a continuous band of colours but contains fine black lines.

The first observations of star spectra were made by Fraunhofer as early as 1824, and later more

extensively by Secchi and Huggins. It was soon found that the stars must be incandescent bodies surrounded by a cooler layer of gases which produce the black lines, and thus must be very similar in structure to the sun. When the black lines were studied in detail they were found to be identical with lines ascribed to chemical elements on earth; furthermore, it appeared from Secchi's work that, with very few exceptions, the spectra of all stars could be arranged in four groups. The first of these groups is typified by the presence of only a few black lines, principally those of hydrogen, while the second group is marked by numerous lines which may be proved to be of metallic origin and due to calcium, iron, magnesium, and other well-known metals. The white stars all belong to the first group, the yellow stars to the second. The red stars are divided over the other two groups and show shaded, banded regions due to titanium oxide, or to carbon compounds, in their spectrum.

As in many other fields, so in the field of stellar spectroscopy visual observations were soon abandoned in favor of photographic spectroscopy which operates not only more efficiently but also produces a record which may be examined at ease in the laboratory rather than in an uncomfortable position behind the telescope. As in the case of direct photographs of the sky, Pickering at Harvard became a pioneer in this work, and photographic observation of star spectra on a wholesale

basis has led to a classification of much greater detail than Secchi's. In the system developed by Miss Maury, Mrs. Fleming, and Miss Cannon ten principal types of stellar spectra are recognized. Classes O, B, and A comprise the former first type, class O stars showing very few lines, class B, lines due mainly to hydogen and helium, while in class A the hydrogen lines alone predominate the whole spectrum. The second type of Secchi is divided into classes F, G, and K, where, in the order mentioned, the hydrogen lines become less and less conspicuous and the metallic lines, principally those of calcium and iron, grow more intense. Class M takes the lion's share of former type III, class N that of type IV, while classes R and S contain but a few stars. Miss Cannon and the late Professor Pickering at Harvard have already classified more than 250,000 stars on this system, published in a catalogue named in honor of Henry Draper, another pioneer of stellar photographic spectroscopy in America.

Originally it was believed that the difference in stellar spectra was due to difference in chemical composition among the stars. Those showing strong hydrogen lines were assumed to consist largely of hydrogen, at least insofar as their upper layers were concerned. Researches by Lockyer and subsequent application of modern physics by Megh Nahd Saha of Calcutta led to the conclusion that the chemical composition of the stars is of negligible

influence on the spectrum, but that the difference in temperature alone is responsible for the fact that in some stars the lighter gases, hydrogen and helium, seem to come to the fore, while elsewhere the heavier metals preponderate.

This explains at the same time why the vast majority of stellar spectra arrange themselves so neatly into one sequence: classifying the spectrum of a star is reduced to a determination of its temperature, and, except for a few cases of strange behaviour, the temperature of the outside layers of a star completely dominate the larger features of the spectrum. From facts known in the laboratory and from experiments conducted on earth with atoms of the different chemical elements it has become possible to conclude that the surface temperature of the coolest stars visible, those belonging to Secchi's type IV, and Miss Cannon's class N, is about 3,200 degrees Fahrenheit. On earth we should still call it "white heat"; in the sky we call stars of this type "very red," since they appear dull red in comparison with other, much hotter stars. Going up in the scale of temperatures, we next find stars of class M, such as Betelgeuse, whose temperature is about 4,800 degrees Fahrenheit. That of the sun, which shows a spectrum of class G, is about 10,000 Fahrenheit, while the white stars, Sirius, Vega, and others, are well over 20,000 degrees. The still hotter stars, belonging to class B and O and having a temperature of 35,000 degrees or

more, even appear blue in comparison with sunlight.

A very interesting application of the theory of stellar temperatures lies in the calculation, by theoretical means, of the diameters of the stars. It has long been known, from the researches of Stefan, Boltzmann, and Wien, that the total amount of light radiated per square inch by a hot body depends almost entirely upon the temperature; for a "complete radiator" this amount of light can be accurately predicted. Once we have measured the temperature of a star from its spectrum, we can thus calculate the amount of light given off per square inch by that star; a comparison of this with the light we receive from the star on earth will yield a resultant value for its apparent size.

It was in this way that Hertzsprung first predicted the sizes of the stars, as early as 1905, when there seemed to be no hope whatsoever of experimental verification: the largest diameters predicted were no more than one twentieth of a second of arc, or as large as a dime seen from a distance of forty miles. Thanks to an instrument invented by Fizeau, greatly improved and successfully applied to astronomical measurements by Michelson, the interferometer, it has become possible in recent years to make actual measures of the diameters of the stars. Using the 100-inch reflector at Mount Wilson, Pease has already measured the apparent angular diameters of seven of the brightest red stars. These are especially suitable for such meas-

urements since, on account of their low temperature, their *surface brightness*—that is, the total light emitted per square inch of the surface—is exceedingly low. Therefore, if they appear bright to us, it can only be because they have a very large surface; thus, they will appear to us with a large angular diameter, "large" meaning one twentieth of a second of arc. For yellow stars the apparent diameter is already much smaller: Arcturus, for example, is no more than one fiftieth of a second of arc in size, and Capella which, square inch for square inch, gives as much light as the sun, but which has an actual diameter ten times greater than that of the sun, appears to be no more than seven one thousandths of a second of arc in size. For the white and blue stars the predicted diameters are so much smaller that there does not even now seem any possibility of determining them by measurement.

Actually, these apparently small diameters of the stars correspond to enormous sizes. Even if Betelgeuse appears to us only as large as a dime at a distance of forty miles, we must remember that Betelgeuse is not forty miles but 25 million million times forty miles distant, and is therefore 25 million million times larger than a dime in diameter, about 250 million miles, 300 times larger than the sun. If the sun, with its attendant planets, were placed in the centre of this gigantic star, the whole orbit of our earth would lie well inside it, and even

that of Mars would not be very much outside. The total bulk of Betelgeuse must be about twenty-five million times larger than that of the sun; on any

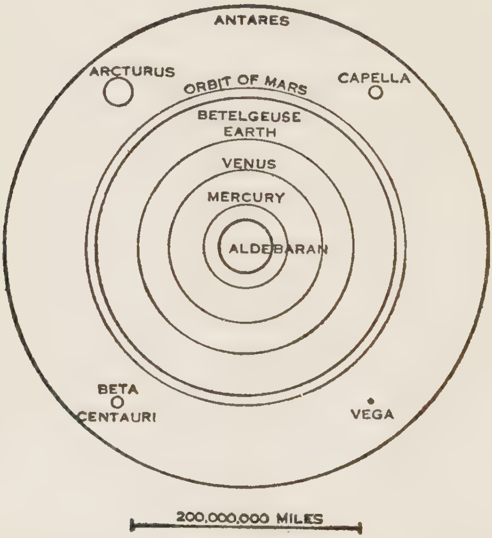


FIGURE 11.—SIZES OF THE STARS I. THE DIAMETERS OF SOME OF THE LARGEST KNOWN STARS ARE HERE COMPARED WITH THE ORBITS OF THE FOUR INNER PLANETS AND WITH VEGA, A NORMAL WHITE STAR OF AVERAGE SIZE.

reasonable assumption of its weight, the mean density must be about one thousandth of our atmosphere. Taken on the whole, this immense red star must be composed of tenuous material more than

one thousand times more rarefied than the gases in our atmosphere; a vacuum we should call it on earth! Pease's measures were a complete vindica-

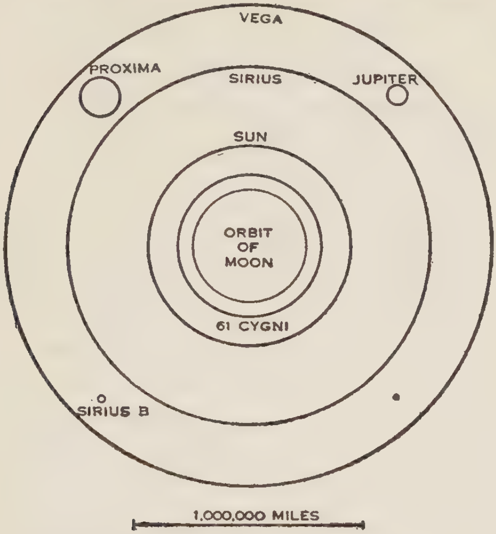


FIGURE 12.—SIZES OF THE STARS II. COMPARISON OF THE DIAMETERS OF THE STARS, INCLUDING THE SUN AND SOME SMALLER "DWARF" STARS, WITH THE ORBIT OF THE MOON AND WITH THE PLANET JUPITER. THE SMALL BLACK DOT AT THE LOWER RIGHT REPRESENTS THE CALCULATED DIAMETER OF THE SMALLEST "WHITE DWARF" NOW KNOWN.

tion of Hertzsprung's early predictions, and astronomers feel confident now that they are not only on the right track in their theories concerning

the temperatures and the total light output of the stars, but also that they can predict with reasonable certainty the diameter of any star for which the temperature is known, and whose light has been measured. The calculated linear diameters expressed in miles are still somewhat uncertain, and a large part of this uncertainty is due to lack of precision in our knowledge of the distances of the stars.

With the problem of stellar distances we are really entering upon one of the most vital points in our study of the universe. On our knowledge of distances rests our conception of the structure of the universe, and it may well be said that the determination of the distances of the stars constitutes the most urgently necessary task and at the same time the most difficult one in all practical astronomy. We have previously mentioned the difficulties encountered in the determination of the distance of the sun, difficulties arising simply from the fact that our baseline for triangulation was no more than 8,000 miles long, a length totally insufficient to measure with accuracy a distance of 93,000,000 miles. Now that we turn to the stars, however, even that distance, a "mere 93,000,000 miles," fades almost into insignificance in view of the fact that the nearest star is 275,000 times 93,000,000 miles away. To try and measure such distances of trillions of miles from a baseline no more than 8,000 miles long is palpably ridiculous. We must look

for other means and other baselines, and fortunately, we do not have to look far.

In the course of its annual motion around the sun, the earth describes a circle with a radius of 93,000,000 miles; consequently, the position in space from where we terrestrials observe the stars does not remain the same. If we look at the sky now, and again in six months' time, we shall then be viewing it from a point, 186,000,000 miles distant from the place of first observation. We shall see that certain very minute changes have taken place. We all know that when we are riding in a train and looking out of the window we see the landscape undergo slow but progressive changes. If we fix our eyes on a church spire, for instance, and on a distant mountain range behind it, we notice that the mountains seem to travel along with us but the church spire appears to lag behind. In its path around the sun the earth does not travel in a straight line, but follows an almost circular orbit. To make our analogy more exact, therefore, we should have to make our train go in a circular track around a centre, the sun, and view our church spire, as one of the nearest stars, against the mountain peaks, acting as the background of very distant stars. Observing from the train, we should see the church spire move to and fro as outlined against the mountains. If, for instance, we look at the church spire while the train is going eastward, the mountains would "follow" us, and the church spire

would appear to be moving westward with respect to the mountains, while at the opposite side of the circular track, where the train would be running westward, the church spire would again appear to move in the opposite direction with respect to the mountains, and appear to go eastward.

Exactly the same motion may be observed in the nearer stars when compared with those more distant: stars situated in a position analogous to that of the church spire, that is to say, stars lying nearly in the plane of the earth's orbit, would be seen swaying to and fro in the period of one year. Stars seen in a direction perpendicular to the plane of the earth's orbit appear to describe a small circle, when compared with the more stationary background, stars in intermediate positions describing ellipses. As is easily verified from the diagram, the diameter of such a circle and the largest dimension of such an ellipse, or the full length of the line along which the star appears to sway, are equal in every instance to the angle subtended by the diameter of the earth's orbit as seen from the star in question. Half this angle, or the angular size of the radius of the earth's orbit, of one astronomical unit, as viewed from the star, is called the *parallax* of the star. We notice from the diagram that the parallax of a star decreases as its distance from us increases.

This apparent motion of the stars in the sky is a necessary consequence of the revolution of the earth around the sun, and the fact that such a mo-

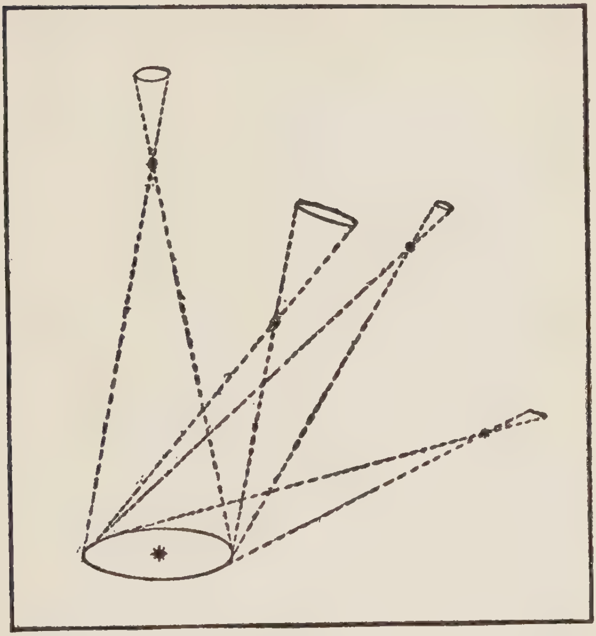


FIGURE 13.—PARALLAX OF A STAR. THE DIAGRAM ILLUSTRATES HOW, AS A RESULT OF THE MOTION OF THE EARTH AROUND THE SUN, THE STARS ARE SEEN TO DESCRIBE ELLIPSES IN THE SKY. THESE ELLIPSES VARY FROM A STRAIGHT LINE (LOWER RIGHT), WHEN THE STAR IS SEEN IN THE PLANE OF THE ECLIPTIC, TO A CIRCLE, WHEN THE STAR IS SEEN PERPENDICULAR TO THE ECLIPTIC.

tion had not been observed was immediately used by the opponents of Copernicus as an argument against his system. In the system of Ptolemy the earth occupied the fixed centre of the universe, and no motions of this kind could be observable among the stars; in that of Copernicus, only the sun remained fixed in space while the earth described a circle around it, and thus, as a result, or rather as a reflection, of this motion of the earth, all the stars should annually describe circles or ellipses in the sky. Copernicus, however, had himself foreseen this difficulty and had met it beforehand: the distances of the stars are so vast that their annual motion in the sky is insensible. Copernicus was right indeed, but we must admit that it was an act of faith on the part of his followers to accept it. For nearly three hundred years the adherents of this theory had to exercise this faith, as it was not until the middle of the Nineteenth Century that their faith was substantiated by facts. Almost simultaneously Struve in Russia, Bessel in Germany, and Henderson in South Africa succeeded in measuring the parallax of a star. It then became obvious that with the older and less precise methods of observation no parallaxes could possibly have been measured. If, returning to our analogy of observing a church spire from a train window, we should have to replace the train running on a circular track by a toy train running in a circle of one-foot radius, and put the

church spire at a distance of fifty miles, even then the church spire would represent only the very nearest of all stars.

When measuring the distances of the stars, the astronomer looks around for a new yardstick with which to express his distances. In the laboratory we measure in inches and feet, while the surveyor uses yards and miles. When we leave the earth behind us, a mile is of little use any more. Even the moon, the nearest of all celestial objects, is 240,000 miles distant, the sun no less than 93,000,000. In the solar system we circumvent the problem of using large numbers by taking this distance of the sun, 93,000,000 miles, as a new unit, calling it one astronomical unit. It does service throughout the planetary system, but no sooner do we pass beyond the frontier of the sun's domain than it sinks into insignificance. The nearest of all stars is 275,000 astronomical units away. We are obliged to devise a new unit for measuring stellar distances, and we choose that distance from where the radius of the earth's orbit would appear to be one second of arc. The *par*allax of a star at that distance would be one *sec*ond: and we call this new unit a *parsec,* a name first suggested by Turner. Seen from this distance, the orbit of Neptune, which constitutes the outermost boundary of the solar system, would appear no larger than a silver dollar seen from a distance of 200 yards.

Another way out of the difficulty lies in making use of the speed of light. Traveling at the rate of 186,000 miles per second, a ray of light could go round the earth seven times in one second. It takes only eight minutes, nineteen seconds for a light ray to reach us from the sun, four hours to penetrate from the sun to Neptune. A ray of light could traverse the whole domain of the solar system in eight to nine hours, but it would require four and one-half years to reach the nearest star. Here, then, we have another chance of establishing a new and convenient yardstick to guage the depths of space: the *light year,* the distance covered by a ray of light in one year, and equal to a trifle more than one third of one parsec. Expressed in miles, a light year equals a number with twelve ciphers, nearly 6,000,000,000,000 miles while a parsec equals almost 18,000,000,000,000 miles.

A star one hundred light years distant has a parallax of one thirtieth of a second of arc; this means that, on photographic plates taken with the best telescopes available, the total displacement of the star due to parallax is no more than one five-thousandth part of an inch. If we wish to have any feeling of security in the determination of such a distance, the least we may ask is that the uncertainties due to measuring shall not exceed one quarter of the quantity measured, that is to say, shall not exceed one twenty-thousandth part of an inch, less than half of one hundredth part of the thickness of

an ordinary playing card. With our best instruments, and taking all the precautions possible, we can barely attain such accuracy, but it is plain that we cannot place great faith in a single measure of the distance of a star with a still smaller parallax, that is of a star more than 100 light years away. Since the pioneer work of Schlesinger at the Yerkes Observatory, and through the concerted effort, during the past twenty years, of several observatories in America, notably the McCormick, Allegheny, and Mount Wilson Observatories, and in England, the Royal Observatory at Greenwich, we now have at our disposal reliable parallaxes of about 2,000 stars. However, it is only too evident that the end is in sight. In fact, no sooner had determinations of stellar distances, perhaps the most fundamental observations in astronomy, begun, than we became aware of the limitations set by the problem itself. We may be able, ultimately, to determine the exact distances of all stars nearer than 300 light years, and perhaps, through accumulation of large numbers of observations made at different observatories, be able to push this limit as far as 1,000 light years, but we shall not, as we now see it, ever be able to extend our researches beyond. That part of the universe beyond 1,000 light years will remain a closed book to us as far as direct determinations of distance are concerned.

However, when direct methods fail, we search for indirect ones, methods based upon the physical

properties of the stars themselves; in the first place, the intrinsic brightness. This is the "real" luminosity of the star, not its apparent brightness, as we see it in the sky, since the apparent brightness is dependent upon the star's distance. As soon as the distance is known, the intrinsic luminosity of a star may be found, since its apparent brightness is always easily measurable. In order to have a standard of comparison, astronomers have agreed to define the intrinsic brightness, or the *absolute magnitude,* as it is usually called, as the brightness under which the star would appear if it were seen from a distance of ten parsecs, or thirty-three light years. Our sun, removed to this distance, would shine as a star of the fifth magnitude, four million million times fainter than it appears to us now. Betelgeuse, on the other hand, would appear much brighter than it is now, and of the magnitude −3, and Rigel, the other bright star in Orion would again outshine Betelgeuse, being of magnitude −6. Thus we see that actually these two stars surpass the sun more than 1,000 and 15,000 times in light, respectively, although, owing to our proximity to the sun, our sun appears to outshine them both by more than sixty thousand million to one.

As soon as the intrinsic luminosities of the stars became known, even though the early measurements of stellar distances were crude compared to the modern ones, a curious relation between luminosity and colour, or temperature, was noted. When

arranging his stars in order of their colour, or spectral class, Hertzsprung found that the whiter and hotter stars were, on the whole, more or less of the same luminosity, while the yellow stars appeared to divide themselves into two groups, a high-luminosity group, and a low-luminosity group, the disparity in intrinsic brightness becoming greater as the stars increased in colour. Thus, the stars of the same spectral class as the sun are seen to cluster around two values of the absolute magnitude, one, which is equal to that of the sun, the other rating one hundred times brighter. Stars as yellow as Arcturus and Aldebaran form two groups that differ a thousandfold in brightness, while the very red stars such as Betelgeuse and Antares appear to have the choice between two groups differing in brightness as much as from ten thousand to one. A further remarkable fact is that the stars constituting the brighter of those groups are of about the same luminosity for all different spectral classes—that is, approximately one hundred times as bright as the sun. Russell has very happily suggested the name "giants" for them. The other stars, the "dwarfs" of Russell's system, decrease very rapidly in intrinsic brightness as their colour becomes more yellow.

We now begin to see an indication of the way in which we can use these facts to derive stellar distances. If, knowing the apparent brightness of a star, we can calculate the intrinsic brightness, once

the distance is known, then, conversely, we can estimate the distance when we know the intrinsic luminosity. If, furthermore, we observe the color of the star, or what is really equivalent, its spectrum, it is then necessary only to know whether the star in question is a "giant" or a "dwarf," and the problem is solved, since, as we have seen, the intrinsic luminosity of the star is then approximately known. The actual solution again finds its origin in a remark made by Hertzsprung in 1907, when he found that in the spectra of the yellow stars a certain black line, due to the chemical element strontium, was more conspicuous for the giants than for the dwarfs. Working in 1913 at the Mount Wilson Observatory, Kohlschütter developed a method by which it became possible to determine the absolute magnitude of the stars from the relative strength of certain lines in their spectrum. Kohlschütter's method was greatly elaborated and extensively applied by Adams and his collaborators at Mount Wilson, and by Young and Harper at Victoria. Their labours have resulted in the determination of several thousand "spectroscopic absolute magnitudes," and hence have greatly augmented our knowledge of stellar distances. The great advantage of the spectroscopic method for deriving distances is that, if once the intensities of the lines in stellar spectra have been calibrated with known intrinsic luminosities, the distance of any star that can be observed spectroscopically may be determined. Instead of standing

helpless with our triangulation methods before an inadequate baseline of only 93,000,000 miles, we now approach the problem well equipped with a powerful spectroscope. Extending our gauges of the depth of space had become tantamount to increasing the light-gathering power of our telescopes. Hence the restriction of 1,000 light years as the greatest distance measurable is removed at once; with the 100-inch telescope a distance of 50,000 light years could be measured with ease.

Chapter X

STELLAR MOTIONS AND THE NEAREST STARS

"Ships that pass in the night."
—LONGFELLOW.

THE "crystal sphere of fixed stars" is no more. To the peoples of ancient times it may have represented the acumen of immobility and repose in its arrangement of perpetual order; for us the individual stars have come to life. To us they represent glowing suns, great globes of matter in constant turmoil inside and, subject as they are to the law of gravitation, in chaotic motion in space, a bewildering picture of perpetual unrest. Indeed, when accurate observations of the positions of the stars are made and compared with others made in the past, it is found that no stars really remain fixed; they all move. Some stars move so rapidly that their displacement among slower, more distant stars may easily be detected; others seem so inert that many years are required to reveal their motion. Sirius, for example, moves more than a second of arc per year, a motion that would carry

it across the moon's disk in 1,400 years, while Alpha Centauri is even more rapid and traverses a distance equal to the moon's diameter in 500 years. Astronomers call this a very large motion; there are, in fact, but few stars in the sky that move with such speed. To the naked eye, on the other hand, even this large motion would be utterly indiscernible, as the following illustration may show:

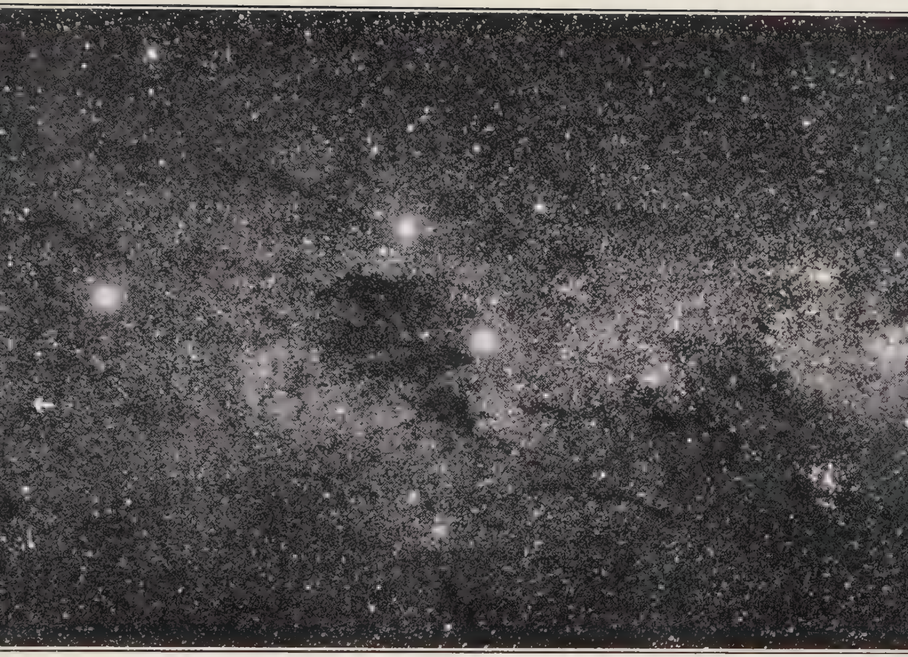
Imagine that, one night, we put a dime on the sidewalk of lower Broadway, in New York City, and place a docile firefly in the center. Suppose further that we ascend to the top of the Woolworth tower, and, taking for granted that the dime as well as the firefly are still in place, observe them from this distance of 800 feet. If we are able to distinguish the firefly and see it crawl from the middle of the dime to the edge in one year, we have observed a motion just as fast as that of Alpha Centauri in the sky. To the unaided eye it may not seem impressive, but the astronomer, armed with a good telescope, could easily determine it in ten days.

Actually, too, this motion is very rapid, for, although it does not appear to us to be more than halfway across a dime per year, that is less than one thousandth of an inch per day, when we view it from a distance of 800 feet we should not forget that Alpha Centauri is not 800 feet but twenty-five trillion miles distant from the earth. In order to cover the same *angular* distance in the sky, Alpha

Centauri must fly with a proportionately greater speed, equal to 14 miles per second, as exact calculation shows.

These angular displacements in the sky are called *proper motions,* to indicate that they are inherent in the stars themselves; they are accurately known for all the stars visible to the naked eye, and for many thousands of others. The largest known proper motion is that belonging to a faint star in the constellation Ophiuchus, discovered by Barnard, and reaches the value of more than 10 seconds of arc per year. Perhaps it should be stressed that large proper motions may be due to two causes: either the star has actually a large motion, expressed in miles per second, or the star is very near to us. Barnard's star belongs to both classes, as it is the second nearest of all stars in space and also has a linear motion of 56 miles per second. Take, on the other hand, the two stars Sirius and Antares, both of which are actuated by a speed of 10 miles per second. Sirius is only 9 light years away, but Antares 360, with the result that Sirius *appears* to move 40 times faster than Antares.

It is, of course, unreasonable to suppose that all the stars are moving sideways as seen from the earth, for in general any moving object, when viewed from a fixed place, will appear to be approaching or receding as well as moving sideways. This other motion, the velocity of approach or of recession, cannot be determined from observations



Photograph Harvard Observatory

PLATE VII

The southern Milky Way, showing the Southern Cross, the Coal Sack, Alpha and Beta Centauri. The Southern Cross, in the centre of the plate, has ceased to be conspicuous as a cross, for the sole reason that one of its stars is very red and does not register well on the photographic plate. The lowest and brightest star of the cross may be seen immediately to the right of the Coal Sack, the black spot in the centre of the plate. The next brightest star is to the left and above, while the red star is straight above the brightest star, and the fourth above and to the right. The bright star near the left-hand edge of the plate is Alpha Centauri, while Proxima, the nearest known of all stars, and a companion in space of Alpha, is one of the many faint stars indicated by the arrow. The distance in the sky between Proxima and Alpha is almost three degrees, corresponding to 11,000 times the distance sun-earth.

of the positions of the stars: if a star were coming straight at us it might appear to be growing steadily brighter, but it would never shift its position in the sky. Fortunately, we have in the spectroscope a means of observing this *radial velocity,* as it is called. The principle underlying such observations is that light is composed of waves similar to those of sound but traveling at a much greater speed, 186,000 miles per second, instead of 1 mile in 5 seconds. If you have ever attentively listened to an automobile blowing its horn while it was rapidly approaching and passing you, you will have noticed that while the car was still approaching, the pitch of the horn was comparatively high, and that it dropped noticeably the moment the car had passed and began speeding away. In the first case the sound waves, traveling toward us with a velocity of 1,000 feet per second, were helped along by the speed of the automobile, which might have been 60 miles per hour, corresponding to about 80 feet per second, while in the second case the sound waves had to overcome the unfavorable speed of the automobile. In the former case, more vibrations reached us per second and the pitch was higher; in the latter case, fewer vibrations reached us and the pitch dropped. If we put a standard tuning fork on the automobile, giving out a C, for example, and compared it with another standard C tuning fork remaining stationary, we

could easily determine the speed of the automobile from the difference in pitch, in each case separately.

The same holds for the light of the stars as Doppler has shown; it too consists of waves, and these waves will be approaching us faster or slower, depending on whether the star itself is approaching us or receding from us. When the pitch of a light wave is changed, that is to say when the number of vibrations per second is changed, the colour of the light is changed: toward blue when the pitch is increased, toward red when the pitch is lowered. Since the speed of light is so excessively high, the corresponding shift in colour is minute and can only be ascertained through very delicate measurements. If there is an atmosphere of hydrogen gas around the star, producing a black line in the green part of the spectrum, the pitch of this black line, too, will be altered if the star has a velocity in the line of sight; if the star is approaching, the line will be shifted toward the blue-green, if the star is receding the line will be displaced toward the yellow-green. If now, when the star is observed, an observation is made simultaneously of the same black line but produced by terrestrial hydrogen gas, a small difference in "pitch" of the line may be accurately measured.

The principle of measurement of the velocities in the line of sight is thus quite simple, but the actual execution of such measures in practice is an entirely different matter. Visual observations be-

gun in England by Huggins were subject to such large uncertainties that they were soon abandoned when Vogel in Germany showed that a much greater accuracy may be secured by photography, but real success in this field was not attained until Campbell at the Lick Observatory applied himself to the problem. Using a powerful spectroscope attached to the 36-inch telescope, Campbell was able to measure velocities with an accuracy of about half a mile per second, corresponding to a measuring accuracy on the photographic plate of less than one ten-thousandth part of an inch. Through the coöperation of many observatories, notably the Lick, Mount Wilson, Victoria, and Cape of Good Hope Observatories, the radial velocities of more than 5,000 stars are now known.

When the radial velocities of stars in different parts of the sky are compared, the fact is brought to light that in some regions the velocities are preponderantly negative—that is, the stars are approaching us—while in the opposite regions the stars are, on the whole, receding. Analysis of the proper motions reveals the same tendency: the stars seem to be approaching the region of the sky near Sirius, and avoiding the opposite part. Calculating the linear speeds in miles per second from the proper motions and the distances, when known, and combining them with the radial velocities, we obtain the total velocities of the stars. At first these total velocities seem to be haphazard, almost chaotic in

THE BRIGHTEST STARS

Name	Constellation	Magnitude	Distance	Luminosity	Temperature	Diameter	Mass	Proper Motion	Radial Velocity
Sirius*	α Canis Majoris	− 2	9	27	20,000	1.8	2.4	10	− 5
Canopus	α Carinæ	− 1	110	2,200	12,000	......	20	2	+13
*†	α Centauri	0	4	1	10,000	1.0	1.1	14	−14
Vega	α Lyræ	0	26	50	20,000	2.4	3	9	− 9
Capella†	α Aurigæ	0	49	150	9,500	12	4.2	20	+18
Arcturus	α Boötis	0	41	100	7,000	30	8	85	− 3
Rigel*	β Orionis	0	460	14,000	23,000	......	50	2	+14
Procyon*	α Canis Minoris	0	11	5	11,000	1.9	1.1	12	− 2
Achernar	α Eridani	1	73	240	27,000	......	5	6	+12
	β Centauri	1	300	3,100	37,000	11	25	11	+ 2
Altair	α Aquilæ	1	16	9	15,000	1.4	2	10	−12
Betelgeuse†	α Orionis	1	240	1,600	5,200	290	20	7	+13
	α Crucis	1	230	1,600	37,000	......	10	10	+ 4
Aldebaran*	α Tauri	1	57	90	5,500	60	4	11	+34
Pollux	β Geminorum	1	32	28	7,000	......	3	18	+ 2
Spica†	α Virginis	1	235	1,500	34,000	......	14	11	+ 1
Antares*	α Scorpii	1	360	3,400	5,200	480	30	11	− 2
Fomalhaut	α Piscis Austr.	1	25	15	17,000	......	2	8	+ 4
Deneb	α Cygni	1	650	10,000	17,000	......	50	2	− 2
Regulus*	α Leonis	1	57	70	23,000	......	3	13	+ 4
Sun	....	−27	8 *min.*	1	10,000	1.0	1.0		

The distances of the stars are given in light years, the luminosities in terms of that of the sun, the temperatures in degrees Fahrenheit. The diameters and the masses are in terms of those of the sun, the velocity at right angles to the line of sight and that in the line of sight are expressed in miles per second. Stars marked with an asterisk have faint, distant companions, those marked with a dagger are close doubles, with the components of comparable brightness. In all these cases the luminosity, temperature, diameter, and mass of the brightest component only is given.

A speed of 1 mile per second corresponds to **1 astronomical unit in 3 years,** or to **1 light year** in 186,000 years.

THE NEAREST STARS

Name	Magnitude	Distance	Luminosity	Temperature	Diameter	Mass	Proper Motion	Radial Velocity
Proxima	11	4.2	0.00009	5,000	....	......	14	....
α Centauri A	0	4.3	1.1	10,000	1.0	1.10	14	− 14
B	2		0.2	7,500	....	0.94		
Barnard's Star	10	6.1	0.0004	5,200	0.2	0.2	56	− 73
Wolf's Star	14	8.1	0.00002	4,800	....	......	35	− 56
Lal. 21185	8	8.3	0.0056	5,700	....	......	36	− 54
Sirius A	− 2	8.9	27	20,000	1.8	2.44	10	− 5
B	8		0.003	13,000	0.034	-0.96		
−12°4523	10	9.3	0.0011	5,500	....	......	10	....
Innes's Star	12	9.6	0.00011	....	....	......	24	....
−7°4003	9	9.9	0.0017	5,500	....	......	12	....
Kapteyn's Star	9	10.3	0.0018	6,800	....	......	80	+150
τ Ceti	4	10.3	0.2	8,800	....	......	18	− 10
Procyon A	0	10.4	5.4	11,000	1.9	1.1	12	− 2
B	13		0.00005	....	....	......		
ε Eridani	4	10.5	0.2	8,800	....	......	9	+ 10
61 Cygni A	6	10.9	0.06	6,400	0.7	0.45	50	− 40
B	6		0.03	6,000	....	......		
Lac. 9352	7	11.2	0.01	5,700	....	......	70	+ 7
Struve 2398 A	9	11.4	0.0035	5,500	....	......	24	+ 1
B	9		0.0018	5,500	....	......		
Groomb. 34 A	8	11.6	0.006	5,700	....	......	30	+ 2
B	11		0.00055	5,200	....	......		
ε Indi	5	11.6	0.13	7,500	....	......	48	− 24
Kruger 60 A	10	12.7	0.0018	5,500	0.34	0.27	10	− 14
B	11		0.00035	5,200	0.3	0.18		
Van Maanen's Star	12	12.8	0.00017	13,000	0.007	......	35	....
Cordoba 29191	7	12.9	0.03	5,700	....	......	40	+ 8
Sun	−27	8 *min.*	1.0	10,000	1.00	1.00		

size as well as in direction, but a closer inspection shows that there is "method in their madness." If we select a large number of stars at random and examine their motions, we again find that, on the average, they are always moving approximately in the direction of Sirius. The fault, however, is not in the stars, but in our sun. It is the motion of the sun in space which makes the stars appear to move in the opposite direction. Imagine, for example, a large number of stars whose motions are really and truly chaotic, without any preference for a particular direction. Place the sun amidst them and assume the sun to be going north. Even though the sun might be going so slow that it would be overtaken by a number of stars, we should still find that, on the average, the surrounding stars would *appear* to go south. The *average* motion of the stars surrounding us is a pure reflection of the sun's motion through space, and if the stars appear to be moving toward Sirius it means no more than that the sun is really moving in the opposite direction. Careful analysis of all the velocities known has led to the conclusion that the exact direction of the sun's motion is toward a point not far from the bright star Vega, and that the speed of this solar motion is approximately 13 miles per second.

With the description of the movements of the stars we have finished our survey of their more important characteristics, and we may now see how our sun and the well-known stars measure up in this

respect. In the first of the accompanying tables are given the principal data for the twenty stars which are of the first magnitude or brighter. The proper name of each star is first given, as well as the usual astronomical designation by constellation; then follow the apparent brightness in the sky, expressed in stellar magnitudes, the distance from the sun in light years, and the intrinsic luminosity, derived from the last two and expressed in that of the sun as unit. The temperature is given, expressed in degrees Fahrenheit, while the next two columns show the diameter and mass, insofar as these have been determined or may be estimated with some degree of probability, both again referred to the diameter and mass of the sun as unit. The last two columns give the proper motion and the radial velocity, both expressed in miles per second. A negative sign in the last column means that the star is approaching us, a positive sign denotes recession. At the bottom of the table similar data for the sun are appended for purposes of comparison.

Such a comparison, especially of the data in the fifth, seventh, and eighth columns, is not very flattering for the sun.

There is but one star in the table that is equal to the sun in light and in size; the others far surpass it. To draw the conclusion, however, that the sun must be a very insignificant star in the universe would be erroneous; a comparison with the first-magnitude stars is not really fair to the sun. These

stars are not at all representative of the stars in space; they appear bright to us, not because they happen to be near, but principally because they are of singularly great intrinsic luminosity: they are the aristocrats of space. A much fairer sample of what to expect from the average star in space we may obtain by taking, not the twenty brightest, but the twenty nearest stars. Here we have to add, *now known*, as it is more than probable that a considerable number of stars in the vicinity of the sun have as yet remained undiscovered, simply because the stars are so faint that their presence has not been detected. What we know and what we may conjecture about these twenty nearest stars is gathered in the second table, arranged in the same way as that for the brightest stars, except that the diameters are now given in miles, instead of in millions of miles.

The two sets of data present a striking contrast. To begin with, they have but three stars in common, Sirius, Alpha Centauri, and Procyon, which three are counted among the lesser lights in the first table but appear as the rulers in the second. The sun, so hopelessly outclassed by the first magnitude stars, ranks high among its neighbours in space. This becomes even more evident when we look at the names of these twenty nearest stars: only seven are bright enough to be seen with the naked eye and to have a constellation name; the remainder have to be designated by the number they bear in certain

star catalogues, or by the name of their discoverer. Several of the stars in this second list are "double," some are even "triple"; for all of these, what is known about the individual components has been entered separately. Since the fainter components of the double stars among the stars in our first list would obviously not properly belong there as they would not be of the first magnitude, all the stars in the first table have been treated as single. We shall have occasion to return to the subject of double stars later.

Two items may be emphasized especially; the first of these is the fact that two stars in the second list, the faint companion to Sirius and "Van Maanen's Star," seem to be of much smaller size than the rest. These two stars, with three others not in the present list, comprise the only five *white dwarfs* now known. They all are very curious objects, their mere existence seeming to be in flagrant contradiction to the laws of physics; yet, when examined more carefully, it is seen, as Eddington has shown, that they not only conform to our present ideas of matter but even constitute one of the best proofs for the truth of these theories.

The companion to Sirius, the best known of all, gives 400 times less light than the sun, and has been shown, from observations made with the spectroscope, to be much hotter on the surface than the sun. Thus it gives more light per square inch than the sun, and from its low total luminosity we calcu-

late that it must be a very small body, not any larger in size than the planet Uranus. On the other hand, we have ascertained that it weighs almost as much as the sun. From the combination of its size and its weight we derive its density and find the amazingly high figure of 27,000 times that of water. This remarkable star is made of such exceedingly dense material that one cubic inch of it weighs about half a ton; it is 1,500 times as heavy as gold! Strangely enough, however, when we examine its light in the spectroscope we find that in the outside layers of the star hydrogen abounds, the lightest of all gases, ten thousand times lighter than water. The explanation? Quite simple, if we only stop to consider that all matter, as the latest physical theories maintain, is really full of holes. Hydrogen, the simplest form of matter, is made up of a very small, and very heavy, central particle, the *proton,* around which revolves another, much lighter particle, the *electron,* the combination forming a miniature planetary system. Other chemical elements, though more complicated, are essentially built up of combinations of protons and revolving electrons.

Under ordinary circumstances these multitudes of electrons whirl around the central core so fast that they set up a barrier through which nothing can penetrate, with the result that the size of a particle of matter is determined by the size of the largest orbit of the electrons. Under normal conditions the size of the smallest particle of hydrogen, of an *atom*

of hydrogen, is about four one-billionths of an inch; consequently, we could never compress hydrogen gas more tightly than by lining up four billion atoms per inch. Compared with the size of such an atom, an electron is again totally insignificant; it is at least 10,000 times smaller, and the whole structure resembles, as Sir Oliver Lodge so felicitously expressed it, "a fly in a cathedral." The best we can do under ordinary circumstances is to compress the atoms until the cathedrals touch; beyond that point we cannot go. Deep in the interior of a star, however, things are different, and conditions are not "normal." Here we meet temperatures of several million degrees, temperatures which have the effect of exciting the electrons into violent agitation, so violent indeed, that instantaneously all the electrons are rudely separated from their protons. The two no longer belong together and each pursues its own destiny, entirely independent of the other: in other words, the walls of the "cathedral" collapse, and all that remain are the "flies." We can begin compressing again, and, instead of finding our limit when the cathedral walls touch, we can now go on until the flies touch; obviously, we can thus attain far greater densities than ever before. Especially, since the walls of the cathedrals were not real walls; they were merely barriers set up by the fast whirling motion of the electrons. In other words, the cathedrals were built of the thinnest tissue paper, the flies made of compressed platinum.

Matter under normal, terrestrial conditions is comparable to a city, built of tissue-paper cathedrals touching each other; under the severe strain of the high temperature inside a star the city has collapsed and only the small flies buzzing inside are left. This is, in all probability, what has happened to the faint companion star of Sirius. In its interior the temperature is so high that the electrons and protons have severed their relationship, and the result is a density of 27,000 times that of water.

According to relativity, a star of this extreme density must affect the rays of light emanating from it, since the strong gravitational attraction at its surface makes the light waves indolent; they vibrate slower, and appear shifted toward the red in the star's spectrum. Observations made by Adams at Mount Wilson have indeed borne out this prediction, thus proving not only the correctness of the calculated high density but also of the relativistic deductions.

The other item of interest in the second table concerns the first two entries, Proxima and Alpha Centauri. The latter, the third brightest star in the sky, has long been regarded as the sun's nearest neighbour in space. In 1911, however, Innes, at Johannesburg, discovered a faint star in the vicinity of Alpha Centauri which showed a large proper motion. Accurate measures proved this motion to be practically identical with that of Alpha itself,

leaving but little doubt that the two stars are connected and travel through space together. When the distance of the new object was measured it was found to be slightly closer to us than Alpha, and thus this faint star, a companion of Alpha Centauri, becomes the sun's nearest neighbour; hence its name, Proxima. The way in which the motions of the stars may be discovered is shown in Plate VIII, where three photographs of the region of Proxima are compared. The left-hand one, taken in 1901, shows Proxima to the left of another star of equal brightness; in the centre picture, taken in 1910, Proxima forms a close double with its apparent neighbour, although this neighboring star may be 100 times farther away. On the right-hand photograph, taken in 1925, Proxima has passed its neighbour by a considerable distance, while the relative configuration of all the other stars in the photograph has remained unchanged.

The large angular motion of Alpha Centauri will gradually carry it into a different part of the sky. In about 4,000 years it will pass very close to its rival, Beta Centauri, thus forming the most spectacular double star in the heavens, while 14,000 years hence it will stand at the head of Southern Cross. In 28,000 years from now it will come closest to the sun, and will then shine as a star of the magnitude minus one. Counting back 2,000 years, we find that at the beginning of our era Alpha Centauri belonged to what is now the constellation

Circinus; had the constellations then been mapped, the star might have been known as Alpha Circini. The case of Alpha Centauri is only one out of many and illustrates the effect of the proper motions of the stars upon the configuration in the sky. In the course of time all relative positions in the sky will be altered; the constellations will be "dislocated." Fifty thousand years ago there was no "Big Dipper"; fifty thousand years hence, the Big Dipper will again belong to the past.

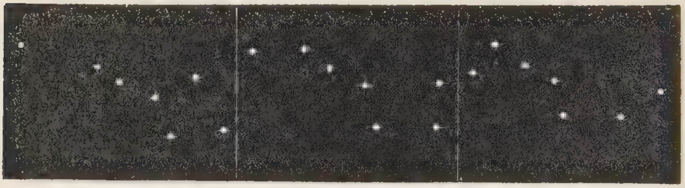


FIGURE 14.—THE CHANGING SKY I. THE BIG DIPPER, AS IT WAS 50,000 YEARS AGO, AS IT IS NOW, AND AS IT WILL APPEAR 50,000 YEARS HENCE.

The companionship of Alpha Centauri and Proxima is not unique in the annals of the sky; we know of many cases where a number of stars appear to be travelling together in space. The most celebrated of them all is undoubtedly that of the group of Big Dipper stars, or the Ursa Major cluster, as it is technically called. Proctor had already called attention to the fact that the five central stars of the seven bright stars that form the constellation of the Big Dipper have motions in the sky that are almost parallel. When later observations showed

that the velocities in the line of sight also were nearly identical, and when, in addition, Hertzsprung noticed that several other bright stars distributed over the whole sky had motions in the same direction and of the same amount as those of the

FIGURE 15.—THE CHANGING SKY II. ALPHA CENTAURI AND THE SOUTHERN CROSS. ON THE LEFT, AS THEY APPEAR NOW. IN THE MIDDLE, AS THEY WILL APPEAR 4,000 YEARS HENCE, WHEN ALPHA AND BETA CENTAURI FORM A BEAUTIFUL DOUBLE STAR. ON THE RIGHT, AS THE DEMOLISHED CROSS WILL LOOK IN 14,000 YEARS, WHEN THE UPPERMOST STAR OF THE CROSS HAS MOVED DOWN A CONSIDERABLE DISTANCE AND ALPHA CENTAURI WILL STAND STRAIGHT ABOVE IT. COMPARE ALSO PLATE VII.

Dipper stars, it became evident that we were dealing with a physically associated group of stars, a moving cluster. Among the stars belonging to this family are Sirius, Beta Aurigæ, Alpha Coronæ, and several others. When a model is made of this cluster of stars, it is found that they form a flat, almost disk-shaped group, at present so situated in space that the sun is near the plane of the disk. The sun, how-

ever, does not belong to this family, and, as seen from the sun, the whole disk appears to be moving with a speed of 11 miles per second, in a direction not far from the bright star Alpha Indi. The stars constituting this cluster are doubtless millions of millions of years old; the fact then that the diameter of the disk is at present no more than 150 light years shows that the motions of the individual stars must be very accurately parallel. Without any question we may assume that these stars had a common origin; equally without doubt we can admit that they are driven by the same hidden force to the same unknown destiny. But to say where and how they originated, or what will be their ultimate fate, is beyond our ken. From the point of view of the universe, they and the sun are but chance acquaintances. Compared with our own ephemeral existence, they may seem to be permanent fixtures of the sky, while in reality they linger but a short while. One million years from now the disk-like formation will have receded enough that we may see it all at once instead of having to find the constituent stars all over the sky. In one billion years the stars will have become lost in the deep abyss of space: ships that pass in the night.

When the motion of the sun is calculated from the systematic behavior of the stars surrounding us, the *true* velocities of those stars may be derived by making an allowance for the solar motion. The resulting velocities of the stars again

look chaotic at first sight. But again, when they are subjected to statistical analysis, regularities are soon discovered; the "traffic laws" of the universe are then revealed. Kapteyn, in Holland, was the first one to notice that there are two favored directions of motion, that there appears to be a main highway in the direction of which many more stars are moving than at right angles. In a way, and very crudely, the situation may be compared to the traffic on Fifth Avenue in New York. There is a constant stream of uptown and downtown traffic, with relatively little motion crosstown. Actually, however, the situation among the stars is much more complicated. To begin with, the thoroughfare does not exist as such. It is only the *directions* of motion that show a strong preference for parallelism to a certain axis; all other directions of motion are still possible, though not as frequent. The direction of this celestial highway seems to point not far from the bright star Procyon.

If the regulations on directions of traffic in the universe are lenient, the restrictions concerning speed limits are much more severe. The sun, we have seen, flies through space at the rate of 12 miles per second, a speed slower than the average; 20 miles per second seems to be a normal velocity, 30 is distinctly fast, and velocities more than 40 miles per second are rather infrequent. Only a few stars still persist beyond 40 miles, some as fast as 100 miles per second, and we know of only one

moving with a speed of more than 600 miles per second. The faster a star goes, the more it begins to avoid certain directions in space; we might almost say that certain directions are forbidden to high velocities, that the speeders among the stars travel on "one-way streets."

With stars existing that are 400 times larger in diameter than our sun, and others which have speeds up to several hundred miles per second, it appears reasonable to ask the question if celestial collisions ever occur, even taking into account the immensity of space at the disposal of the stars. The *average* star, as we now think of it, is probably a little smaller than the sun, a little lighter, and moves a little faster. If we make a model of the universe to the scale of one to thirty thousand million, that is to say, if we represent the average star by a billiard ball and place this billiard ball on top of the Woolworth tower, we must then put the next nearest star, also represented by a billiard ball, in San Francisco. To complete the picture, we must endow these average stars with their average motion, 20 miles per second; but, on this small scale, 20 miles per second corresponds to only 2 miles per century. The traffic laws for speeds of 20 miles per second are not very strict in the universe; stars with such speeds may move in practically every direction they please. If then, we let a number of billiard balls as far apart as New York and San Francisco strike out in almost any direction they

choose, but with a speed reduced to 2 miles a century, we have very nearly a true model of the universe. With the situation being such, it does not require much calculation to estimate the frequency with which collisions happen in the universe; it is plain that they must be exceedingly rare. In the whole universe a collision probably does not occur more often than once in many billions of years.

Chapter XI

DOUBLE STARS, VARIABLE STARS, AND NOVÆ

> "Age cannot wither her, nor custom stale
> Her infinite variety."
> —ANTHONY AND CLEOPATRA.

IT WAS known even to the Arabs that Mizar, the middle star of the handle of the Big Dipper, is accompanied by a fainter star, slightly toward the north and visible to a trained eye, although the casual observer might well overlook it. Great was the surprise, however, of the Italian astronomer Riccioli when, in 1650, he turned his telescope on these stars and found that the brighter one again separated into two. After Riccioli's discovery, a few more double stars were casually noted during the Seventeenth and Eighteenth Centuries, but systematic observation of them did not begin until Sir William Herschel entered the field. During a few years of observation he catalogued as many as 700 doubles, while Wilhelm Struve, observing at Dorpat, and Pulkova, in Russia, subsequently published a list of more than 3,000 such stars. Since

then, astronomers have paid a great deal of attention to these interesting objects, and at present more than 20,000 double stars are known.

With the great telescopes of our times stars may be found to be double when the separation between the two components is no more than one or two tenths of a second of arc—about the same as the separation of automobile headlights if these could be seen from a distance of 800 miles. Especially Burnham at Yerkes, and Aitken at Lick have found many such close pairs. Where the telescope fails, the interferometer, the instrument used for measuring stellar diameters, can still be made use of, since with it angular separations as small as one hundredth of a second of arc may be detected under favorable circumstances. So small a separation would correspond to our automobile headlights removed to a distance of 12,000 miles from us, or to two beacons, sixty feet apart, placed on the moon. Even an instrument as delicate as the interferometer has its limitations, however, and double stars closer than this limit of one hundredth of a second of arc would remain undiscovered, were it not for the spectroscope. This instrument, though unable to separate the two components, can yet indicate duplicity. When a seemingly single star is in reality a close double, its two components will, under the influence of their mutual attraction, revolve around each other; and thus, if we consider their centre of gravity as fixed, the two stars will each, in the course

of their revolution around this centre of gravity, alternately approach the earth, or recede from it. Consequently, the radial velocities will vary periodically, and the black lines in the spectrum of the star will periodically shift their positions. From a careful analysis of these changes in the positions of the black lines it may then be ascertained how long it takes the stars to revolve about each other, and the whole orbit of such a *spectroscopic binary* may be reconstructed in detail. Though the two stars may be so close together that we could not distinguish them separately even with our best telescopes, we can yet prove that there, at the immense distances in the stellar universe, two suns are whirling around each other, obeying the law of universal attraction.

Not only the components of a spectroscopic binary revolve around each other, but such motion applies equally to a double star visually observed. William Herschel was perhaps the first to notice that in the course of time small changes occur in the relative positions of the components of a double star. In some cases it is quite evident that one star is revolving around the other, and when mathematical analysis is applied to the observations it is found that the path described by the one star is always an ellipse which has the other star in one of the foci. Thus the attractive force that operates between the components of a double star and compels them to revolve is entirely similar to that which makes the planets describe ellipses around the sun. In fact,

observations of the motions of double stars constitute a beautiful proof for the generality of Newton's law of gravitation, since it can be proved that Newton's law is the only one that can make one star describe an ellipse with the other star in the focus.

Having come to the conclusion that Newton's law of gravitation is universal, we can in turn use it to determine the weight of the stars, from the behaviour of double stars. If we take the case of Alpha Centauri, for example, we find that we are dealing with two stars revolving around each other in 79 years, in an ellipse with a greatest diameter of 4,000 million miles. This is quite comparable to the case of the sun and Uranus, the latter revolving around the sun in 84 years, in an ellipse with a diameter of 3,600 million miles. We know that the attraction between two stars diminishes rapidly as the distance between them increases; smaller distances will thus result in quicker rotation and shorter periods of revolution. We know likewise that the force varies directly as the weight. Taking all this into account, it is easy to see how, from such a comparison as we have made between Alpha Centauri and the system of the sun and Uranus, it is possible to calculate the weight of Alpha Centauri. Similarly, the weight of all binary stars, for which the distance between the components and the time of revolution is known may be computed. The relative motion of double stars provides us with the

only means of determining the masses of the stars and, thus, with a means of "weighing" the universe.

From the data accumulated up to the present, it has been brought to light that the stars are, on the whole, very similar in mass. We have not yet found a star weighing less than one tenth as much as the sun; likewise, stars more than twenty times as heavy as the sun are scarce, though a sporadic few have been found with masses ranging up to almost one hundred. Comparing this with the tremendous range in luminosity among the stars, from less than one ten-thousandth part of the sun's light to more than ten-thousand times as much, both extremes being reasonably common, we see that indeed the stars have much less disparity in mass than in light, that they are much more alike in substance than in appearance.

The mass of a double-star system can only be found if the system can be properly compared with that of the sun and its planets, that is when the linear distance between the components of the double star is known. The angular separation is always measurable, and the linear distance between the stars thus becomes dependent on the measurement of the distance of the double star from us. Without this distance the mass cannot be computed. From the fact, however, that there is such a small disparity in mass among the stars, Hertzsprung and Russell have reversed the problem, and, by supposing the mass of a double star to be equal to the mean

value for all stars, calculated the distance from this mass. Distances derived in this way are very reliable and often more accurate than direct determinations.

Not all double stars revolve around each other; some seem to move in a perfectly straight line with respect to each other. This does not mean, of course, that Newton's law does not hold in some cases, but simply that the two stars seen as a double star from the earth are not connected at all. They are merely two individuals of the manifold population of the cosmos that happen to be *seen* in nearly the same direction; actually, one may be very near and the other far behind it. Such double stars are called *optical* doubles, in contrast to the real, *physical* doubles. Vega, the brightest star in Lyra, is an example of such an optical double. The proof that the stars are not connected rests, in this instance, upon the fact that the faint companion does not share in Vega's large proper motion in the sky.

Of all the double stars in the sky, Mizar, or Zeta Ursæ Majoris, as the astronomers call it, has made most history. Its name is written on three milestones along the astronomical road of progress. It was the first double star to be discovered with a visual telescope; it was the first double star to be recorded photographically, by Bond at Harvard, in 1857, and it was the first spectroscopic binary to be detected, by Pickering in 1889, also at Harvard. Later, observations by Frost at Yerkes have shown

that both components of the bright star are spectroscopic binaries, and that in addition Alcor, the fainter companion just visible to the naked eye, is also spectroscopically double. Castor, the second brightest one of the Twins, was found to be a double star as early as 1719. As yet the precise period of revolution has not been determined but is estimated to be between 300 and 350 years. Both components of this double are again spectroscopic binaries, with periods of 3 and 9 days respectively, while at a considerable distance from these four stars is situated another faint, red, dwarf star, undoubtedly belonging to the system, and one which is itself a double star.

The brightest star in the sky, Sirius, is unique in that it is the first star for which the existence of a faint companion was computed before it had been observed. We have learned before that Sirius has a large motion in the sky; so large that, as seen by an observer standing on top of the Woolworth Building, Sirius, when watched for a whole year, would be found to move by the thickness of a half dollar placed on Broadway. In this motion, however, Sirius was not regular; instead of moving in a straight line, it swayed to and fro perceptibly. This could not be tolerated; no other star in the universe behaved this way, and the cause of it must be found. Again, as in the case of Uranus and Neptune, astronomers set to work and found that these idiosyncracies of Sirius could

only be explained if it had a faint, but rather heavy, companion which moved around it in 50 years and persisted in pulling Sirius out of its place. When a telescope was turned on Sirius, the companion, 10,000 times fainter than the primary, was found in its predicted place. Subsequent developments have helped to make this faint object one of the prize exhibits in astronomy, since it has a density of 27,000 times that of water.

Concerning the numbers of double stars, it has been found that one in nine among the stars visible to the unaided eye is a visual double, while at least one in eighteen of the stars brighter than the ninth magnitude can be seen to be double. If spectroscopic binaries are included these numbers are still more increased: duplicity must be rather common in the universe. Naturally enough, these double stars revolve around each other in all kinds of ellipses, with the planes of their orbit oriented at random, in all different ways. Some of those ellipses we see from above, so to speak; others we view obliquely, with the result that they appear foreshortened; still others we see "on edge." Suppose now that such a double star, or rather a spectroscopic binary, because there the two stars are closer together, consists of a small, very luminous star revolving around another, much larger, and comparatively dark star. If we really see the orbit from the side, the luminous star will, once during every complete revolution around the larger star,

pass behind it and suffer eclipse. Consequently, the total light of the star (which is all we can observe, since the components of such a star are too close together to permit us to distinguish them separately) will be appreciably diminished. When, on the other hand, the smaller and more luminous star passes in front of the larger star, it will in turn hide and eclipse a small fraction of the light of this larger and fainter component. Since a large portion of the total light is concentrated in the small star, the diminution of light in the latter case is only small.

Such an eclipsing system we find in Algol, the second brightest star in Perseus. Here, a star 100 times brighter than the sun periodically passes behind and is eclipsed by a slightly larger star only about ten times as bright as the sun. When the two are side by side, and the full light of both of them reaches us, Algol shines as a star of the second magnitude; the partial disappearance of the brighter star will make the magnitude drop to between the third and fourth, or to about one third of the normal amount of light, while the secondary eclipse, when the bright star is in front, diminishes the combined light by only 4 per cent. In the accompanying figure we have tried to give a representation of what occurs in the case of the star RW Tauri, another "eclipsing binary," which is invisible to the naked eye but shows a greater change in brightness than Algol. It is clear from the drawing that during

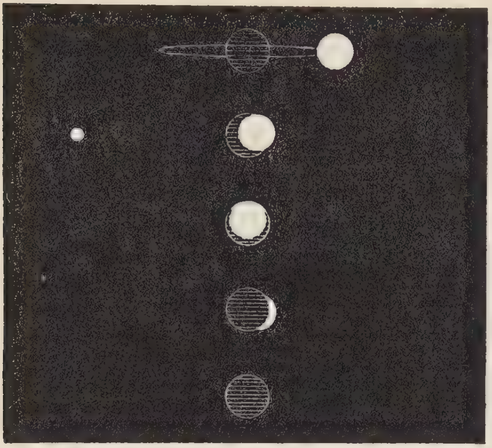


FIGURE 16.—AN ECLIPSING STAR. AT THE TOP IS SHOWN THE ORBIT OF THE SMALLER AND BRIGHTER STAR AROUND THE LARGER AND FAINTER. BOTH STARS ARE FULLY VISIBLE, ALTHOUGH, OWING TO THEIR TREMENDOUS DISTANCE, THEIR LIGHT COMBINES INTO ONE AND THE SYSTEM APPEARS UNDER ITS MAXIMUM BRIGHTNESS. IN THE SECOND PICTURE THE BRIGHTER STAR IS PARTLY IN FRONT OF THE FAINTER STAR AND THE TOTAL LIGHT IS REDUCED TO 97 PER CENT.; IN THE THIRD, IT IS REDUCED TO 96 PER CENT. THE FOURTH PICTURES THE BRIGHTER STAR IN THE ACT OF DISAPPEARING BEHIND THE FAINTER ONE, WITH THE RESULT THAT THE LIGHT HAS DECREASED TO 28 PER CENT., WHILE IN THE LAST LINE THE BRIGHT STAR HAS SUFFERED A COMPLETE ECLIPSE, AND ONLY 4 PER CENT. OF THE TOTAL LIGHT REMAINS. THE SMALL DOT ON THE LEFT INDICATES THE SIZE OF THE SUN, DRAWN ON THE SAME SCALE AS THE OTHER STARS.

the greater part of the time the two stars are visible side by side and the combined light must remain constant. When actual measures of this total light are made with a photometer and these measures are plotted in a graph, against the time at which they were made, a series of points are obtained. When these points are joined by a smooth curve, the *light curve,* our predictions are indeed borne out; for the light curve will be flat over the largest part of the period, indicating that no change occurs in the total light, and will further show two minima, a deep one for the primary eclipse, and a shallow one for the secondary.

At present about 200 stars of this eclipsing type are known; among them all different degrees of light variation are found, owing to the necessarily different positions under which their orbits in space are viewed from the earth, and owing to the great diversity in the brightness and size of the components. In the case of Beta Lyræ the two stars are almost, in that of W Ursæ Majoris they probably are, in actual contact; in the latter case the stars are even elliptical in shape.

The light variations of Algol and of many other eclipsing binaries are so conspicuous that they can easily be seen with the naked eye. No wonder, therefore, that Algol was discovered as a variable star as early as 1667, by Montanari, in Italy. The real nature of the variability, however, was not brought to light until 1782, when Goodricke and

Pigott took up the problem. In recent years mathematical analysis has been applied to the light curves of these variables, and especially through the work of Russell and Shapley at Princeton a great deal has become known about the properties of the individual stars.

Variable stars of the eclipsing type are, in a sense, not really variable; they only *appear* so, dependent upon the orientation of their orbit in space. Neither of the two components really varies in light output, and this feature distinguishes them from other real variable stars. The explanation of an eclipse does not satisfy the conditions of change of light in the other known types of variable stars; here we have to assume that the luminosity of the star is subject to inherent changes, although we can, at present, only conjecture as to the exact nature of these changes.

Among these other real variable stars, Mira, one of the brightest, was also the first one to be discovered. In 1596 Fabricius, in Holland, noted a star of the third magnitude in the constellation Cetus, which faded rapidly and disappeared in a few weeks. It was again seen in 1603, and for the third time in 1638. So great was the astonishment at the recurrence of such a phenomenon that the star was given the name Mira, the wonderful, a name which it has kept until to-day. For a long time Mira and the subsequently discovered Algol remained the only

ones known; at the close of the Eighteenth Century hardly a dozen were known. One hundred years later, photography had entered the field of astronomy, and more than 500 variable stars were known. At present the total number has grown to more than 6,000, more than 4,000 of which have been found at Harvard. Again mass production has reduced discovery to a commonplace: finding new variables is no longer an event, and anyone with a large collection of photographic plates at his disposal could easily guarantee to find one new variable a day.

When first seen, Mira Ceti was of the third magnitude; later it became invisible to the naked eye. Modern observations have shown it to descend to the ninth magnitude, while it has been known to become brighter than the second. Its total range in brightness, therefore, is more than seven magnitudes, corresponding to a light ratio of one to one thousand. In addition, these light changes have been found to be periodic; not quite as regularly so as the variation of eclipsing stars, but more in the manner of the periodic recurrence of sun spots. Roughly speaking, Mira is at its brightest every 330 days, then spends 240 days in descending to minimum brightness, and consumes only 90 days in its ascent to the next maximum. In every individual cycle of its variation the star does not follow this schedule very closely; it may be as many as twenty days ahead or behind. At present about 2,000 stars behaving in a manner similar to that of Mira are

known, and periods have already been derived for more than 800. When these periods are examined it is shown immediately that the vast majority of them lie between 100 and 400 days, with a concentration around 250 to 330 days. Since these periods are much longer than those of other types of variables, the Mira Ceti stars are usually called long-period variables. Observations with the spectroscope reveal them all as red stars, mostly of spectral class M while determination of their distances and the actual measurement of the diameter of Mira proves that, at least during their time of maximum light, they are among the largest of stars, as large or larger in diameter than Betelgeuse or Antares. They are true giants, and at their maximum luminosity surpass the sun several hundred times in light, while in minimum their light must be comparable to that of the sun. Their speeds are large, more than 40 miles per second on the average, but some go as fast as 250 miles per second.

The next largest group of variable stars is formed by those stars whose light fluctuations are less than one magnitude on the average, and whose periods are usually short, from three to seven days. The brightest representative of this class is the Pole Star; the earliest one for which the light variations became accurately known is a fourth-magnitude star in Cepheus, Delta Cephei, after which the entire group are named *Cepheids*. Unlike the Mira variables, the Cepheids are rigorously periodic in

their light variations; they repeat themselves with such extreme accuracy that the light curve is subject to very precise determination. Although the cause of their variation has not yet been definitely settled, it seems highly probable that the Cepheids are pulsating stars, according to a theory originally proposed by Shapley, and subsequently worked out mathematically by Eddington.

A third group of variable stars, known as the *cluster variables,* because of their occurrence in large numbers in stellar clusters, have periods closely concentrated around 13 hours as a mean. They show light fluctuations very similar to those of the Cepheids, but are less rigorously periodic, subject rather to sudden and erratic jumps. These cluster stars may in some way be physically related to the Cepheids, though many points on which they differ may be cited: The regular Cepheids all have small velocities, usually not more than 8 or 10 miles per second, while the cluster variables are among the fastest stars known, having speeds ranging up to 800 miles per second. The Cepheids are all crowded near the Milky Way; the cluster variables may be found all over the sky.

In 1912, when studying the light variations of some Cepheids among the 2,000 variable stars in the Magellanic Clouds, Miss Leavitt at Harvard noted the remarkable fact that the periods of these Cepheids stood in a distinct relation to their apparent brightness. Since the variable stars all presum-

ably belonged to the Cloud, and were thus at the same distance from the earth, this meant that the periods were related to the intrinsic luminosities. This curious relationship lay unknown for some time, and it was not until Hertzsprung grasped its full significance that it took its rightful place as one of the most powerful means of penetrating the depths of space. Shortly afterward it was extended by Shapley to the cluster-type variables and applied with success in measuring the universe.

If indeed the period of variation is correlated to the intrinsic brightness of a Cepheid, then it is sufficient to determine the luminosity of but one Cepheid, and the intrinsic luminosities—and with them the distances of all Cepheids whose periods of variation have been observed—may be calculated. Hertzsprung had previously shown that the Cepheids may be counted among the brightest stars in the universe, being about 1,000 times more luminous than the sun. This is another incidental advantage of the method, since it means that Cepheids can be seen at far greater distances than ordinary stars, and thus they provide a very efficient and deeply penetrating astronomical yardstick. Perhaps, as the best description of the method of using Cepheids, Jeans's graphic illustration may here be cited: "The method is simply that of a mariner who estimates his distance from land by identifying a lighthouse, looking up its candle power in a book of reference, and

noticing its apparent brightness at the spot where he happens to be."

The long-period variables, the Cepheids, and cluster-type stars, and the eclipsing binaries form by far the largest portion of all known variable stars; the remaining portion consists of stars varying in an irregular fashion. Among these is another group of stars that are not really variable, but only appear so because they are imbedded in an envelope of obscuring material. If this envelope, which is hardly ever uniform in light-obstructing power, moves, it will change the thickness of the occulting curtain in front of the star, and thus give the star the appearance of variability. In the Orion nebula a number of variables are known, which, in all probability, change in brightness for this reason. Another star of this type, discovered by Knox Shaw at Helwan, is situated in the blackest part of a dark cloud in the constellation Corona Australis. It was later found again at Harvard, and varies irregularly between the thirteenth and eighteenth magnitudes.

The vast majority of variable stars behave so regularly that their actions may be predicted with some degree of certainty, and even the most erratic ones will always stay within certain bounds. Compared with such commonplace and monotonous behaviour, we can, however, contrast something that is really new and unexpected: the appearance of a "new" star. Where before there was but an invisi-

ble and unknown denizen of the cosmos, there now appears a star so bright that it may outshine all others in the sky, a *nova,* as astronomers call it. Here we have a real display of the forces of Nature, an explosion which, in a few days, or even hours, may transform an object of comparative insignificance into one of absolute though ephemeral supremacy in the universe.

What really happens, and how? Thus far we can only surmise; we still grope in the dark about the true origin of a nova. How is the stage set for this, Nature's greatest drama? We do not know. Probably it happens in the interior of the star, and in the silence of empty space. While the celestial dynamite is being stored up, slowly but surely, no outward sign betrays what is going on. When the hour strikes, the trigger is pulled mysteriously and the explosion is immediate, but silent, for the voids of space do not admit of any sound. The most spectacular explosion in creation, it is no more than a blinding flash, without the roll of thunder! In one great leap, the hot gases come rushing out, the star begins to expand at the rate of 1,000 miles a second. Within a day it may have increased its light a millionfold, its volume a billionfold. If it was a dwarf before, not unlike our sun, it now has become a giant among giants; for the moment of its glory it has no rival in the realm of transparent space. Meteoric as was its rise, its downfall must soon follow; a few hours, a few days

at most, its brief reign may last. But what are a few days? A mere cosmical instant. The star's brilliance begins to decline, and though the star is unwilling to sink into oblivion again, and may make a few more futile attempts to regain the summit of its former splendor, it is doomed. It may be a matter of months, sometimes of years; the end is inevitable, the grave always claims its prey.

As yet we do not know what causes the outburst of a nova. It cannot be due to a collision between two stars, since such collisions will not happen, on the average, more than once in a million years, and we observe novæ at the rate of at least one a year. Neither can it be due to the passage of a star through a nebula, as the heat generated by friction accumulates too slowly to produce such an instantaneous and immense increase in luminosity. And thus, cornered, with no explanation to offer, we are driven into the star's interior, and must attribute the explosion to the action of mysterious forces in the innermost layers of the star. Although we thus still grope in the dark when it comes to explaining the cause of the outburst, our knowledge of other characteristics of the phenomenon of new stars has advanced rapidly in recent years, especially through the researches of Wright and Lundmark.

The first new star to be scientifically and systematically observed was the one that appeared in 1572 in the constellation Cassiopeia. It was seen by Tycho Brahe, the famous Danish astronomer,

and still bears his name. At the height of its lustre this nova surpassed even Jupiter in splendor and was easily visible in broad daylight. When we now search for it in the spot where Tycho observed it, we cannot find a star brighter than the twelfth magnitude, and it is doubtful whether the remains of the nova are at all visible. At the very least this represents a drop in brilliance of more than seventeen magnitudes, a light ratio of six million to one! Another well-known nova was that of Kepler, appearing in Ophiuchus in 1604, which reached a brightness almost equal to that of Jupiter, and remained visible to the unaided eye for eighteen months. In 1918 a star in Aquila, which theretofore had been of the tenth magnitude, suddenly increased to magnitude minus one, 300,000 times brighter than the sun, actually. The outer layers of this star were expanding at the rate of 1,000 miles per second.

A curious feature developed around the nova of 1901, a diffuse, extended patch of light which appeared to be expanding with a speed of more than 100,000 miles per second. Such a speed was unheard of; it simply could not exist. Kapteyn immediately suggested the explanation: the star was surrounded by a cloud of dust, and as the light from the nova travelled outward, it illuminated these dust clouds in order of their distance from the centre. For the first time in history we *saw* the actual speed of light!

The most recent of brilliant novæ was Nova Pictoris, born in May, 1925. Previously, it had been a star slightly fainter than the sun, intrinsically, and also a little smaller in size, somewhat cooler, and appearing as a star of the twelfth magnitude. On May 25th the nova had suddenly increased its diameter to 40,000,000 miles, 50 times larger than the sun. On June 9th it was of the first magnitude, and almost 80,000,000 miles in diameter. At present (May, 1928) the star has already decreased to the seventh magnitude and is no longer visible to the unaided eye.

Perhaps the most significant thing about new stars is their great frequency of occurrence. Even with our present incomplete surveys of the heavens, we catch a nova rather more often than once a year, and since we can only find the brighter ones, the total number actually appearing must be greater. We know that our earth alone has existed for at least five hundred million years and the sun for many billions of years. It does not seem reasonable to suppose that we are living at a time particularly favoring novæ, and it seems that we have every right to assume that outbursts of novæ have been as frequent during the past fifty billion years as they are now. During that time then, more than fifty billion novæ should have appeared, a number at least equal to what we now estimate is the total number of stars in the universe. This leaves us with two alternatives: either all stars have been

Photograph Harvard Observatory

PLATE VIII

Above: Three photographs illustrating the proper motion of Proxima Centauri. (See page 166)

Below: Nova Pictoris. (See page 208)

Since the scale of the last photograph is more than twice that of the other two, it gives the appearance as if Nova Pictoris were brightest on this last picture. In reality it represents a brightness ten times fainter than that of the middle photograph.

novæ, or will in time become novæ, or "once a nova, always a nova." Either the nova stage is something which every star has to go through at least once, or it is a habit, a disease, which, once contracted, returns time and time again. Although at present there seems to be little or no evidence either way, astronomical opinion in general appears to favor the second notion.

In Plate VIII are gathered three photographs of this nova, the left-hand one showing it as it appeared before its explosive rise in brightness as a star of the twelfth magnitude (February 29, 1902). In the middle Nova Pictoris is shown as it appeared on September 19, 1925, four months after its greatest splendour, when it had already faded to less than one tenth of its maximum brilliance. On the right is given a much more enlarged photograph, taken on December 19, 1927, showing the nebulous envelope which subsequently developed around the star, then more than one trillion miles in diameter.

Chapter XII

CLUSTERS AND NEBULÆ

"If shape it might be called, that shape had none."
—MILTON.

WHILE cruising through the vast emptiness of space the stars are not all subjected to solitary confinement. Instead, they show a distinct tendency to gregariousness. Some, such as Alpha Centauri, are double, or have a faint, distant companion star; others, after the manner of Sirius, are double, but at the same time belong to a larger family of stars, a *cluster*. This family of Sirius, the Ursa Major cluster, has so far as now known, some twenty members, mostly bright stars. They appear bright to us because they are near, and because they are so near that the sun lies almost among them, they also appear scattered over a large part of the sky. When in the course of time the cluster has moved away from us sufficiently that we may view it in retrospect, we shall see a number of stars, not quite so bright as the cluster stars appear to us now, but much closer together; their clustering will then be very evident. Another group of stars, which already

is in this position, is the Hyades, situated at a distance from us of 150 light years, and appearing as a rather closely packed group of stars of the fourth and fifth magnitudes, surrounding Aldebaran in Taurus. The Pleiades, also in Taurus, are still farther away, some 400 light years distant, and as a result they appear more closely packed even than the Hyades. After the Pleiades comes the double cluster in Perseus, a twin conglomeration of stars of the eighth magnitude and beyond; finally we come to the large number of small groups of stars that are known under the name of *open clusters*. Most of these clusters are rather faint, and can only be seen through large telescopes; they contain from a few hundred to at most a few thousand stars, usually with the brightest stars near the centre. Most of the stars in such clusters are intrinsically much more luminous than the sun. About two hundred of such objects have been discovered up to the present.

Another type of cluster, built on a vastly more magnificent scale than these open clusters, is formed by the *globular clusters*. Here thousands and tens of thousands of stars unite into one great conglomeration, a whole firmament in one. These clusters do not, however, reveal their beauty to the naked eye, nor even when seen through a small telescope. Only one, Omega Centauri is visible to the unaided eye as a rather hazy star of the fourth magnitude, while a small telescope still shows the majority of clusters as hazy objects, without much detail, and

with but a few individual stars in their midst. Seen through a large telescope, such a cluster may finally appear to be resolved in all its individual stars, but the photographic plate proves that this resolution is, indeed, only apparent. Long-exposure photographs taken with the largest telescopes show the number of stars to be so great in the centre that the images overlap and create the impression of one tremendous globe of luminosity breaking into stars at the edge.

The very multitude of their stars gives these globular clusters an impregnable appearance, as if to defy all analysis. No wonder that our knowledge of these objects advanced but slowly, almost imperceptibly at first. No sooner were the great telescopes of Mount Wilson turned on them, however, than the barrier was broken down, and through the epoch-making work of Shapley many of the secrets of globular clusters were quickly unveiled. Bailey, at Harvard, had found large numbers of variable stars in these clusters, studied their behaviour, and derived periods for the light-variation of many stars. Combining Bailey's discovery with Hertzsprung's work on the intrinsic brightness of such variable stars, Shapley was able to determine the luminosities of several stars in globular clusters, and thus, also, the distances of the clusters themselves. The globular clusters proved to be among the remotest objects yet found, the nearest and brightest of them all, Omega Centauri, being 21,000

Photograph Harvard Observatory

PLATE IX

Omega Centauri, the nearest of all globular clusters, 21,000 light years distant. It contains thousands and tens of thousands of stars of the thirteenth magnitude and fainter. The combined light of all these stars makes the cluster appear to the naked eye as of the fourth magnitude, as bright as the faintest of the seven stars in the Big Dipper.

light years distant. When removed to such an enormous distance, the sun would appear as a star of the nineteenth magnitude, 100,000 times fainter than the faintest star visible to the unaided eye. And this distance concerns the *nearest* of all globular clusters. On the average they are four to five times farther distant, while the remotest of them all, so far measured, is no less than 200,000 light years away. No wonder that the introduction of such distances immediately placed the globular clusters on the outskirts of creation and revolutionized our concept of the extension of the universe.

The majority of the variable stars in globular clusters complete their cycle of light variation in thirteen hours, and in many cases the light changes appear to take place with almost clock-like precision for thousands of oscillations. Indeed, as Professor Bailey so aptly put it, "these cluster variables might be called Nature's celestial time-keepers"; they would serve, if needed, as admirable watches. If a photograph of a cluster containing a number of such variable stars had been buried with King Tut-Ankhamen, it might be made to reveal the exact epoch when the photograph was made.

The brightest stars in a globular cluster are probably of the same type as the "red giants" in the neighborhood of the sun, similar to Antares and surpassing the sun in luminosity by more than a thousand to one. The individual stars in such a cluster must be very closely packed; a space which

contains one star in the neighborhood of the sun would have to accommodate one hundred in the globular clusters. Even so, the stars are far enough apart to avoid collisions, nearest neighbors being probably no closer than one thousand times the distance between the sun and Neptune.

Owing to their great distance, it has been impossible thus far to determine the proper motions of the globular clusters; at the same time, their faintness has made radial velocity observations extremely difficult. Slipher, at the Lowell Observatory, has determined radial velocities for about twenty of the more than seventy globular clusters now known. These velocities are all large and lead us to believe that the speed of the average globular cluster may be as high as 150 miles per second.

Surpassing in splendour even the globular clusters are the *nebulæ,* those strange, seemingly shapeless clouds of matter, impressive through their evident immensity. Sometimes they appear luminous, creating the impression that they are the cosmic laboratories where stars are being generated; sometimes they are black, contrasting strangely with the myriads of luminous stars surrounding them, and through their omnipresence tragically suggestive of a celestial morgue. For centuries their existence, their constitution, and their rôle in the universe have been an enigma, and although the complete solution will undoubtedly take many centuries more, we feel

confident that now we understand many of its major aspects.

William Herschel, the father of modern astronomy, noted early the fact that there are nebulæ and nebulæ. Not all objects that appear hazy and diffuse in a telescope are real nebulæ. Some are simply conglomerations of stars, star clusters, ultimately resolvable in a large telescope, while others appear obviously gaseous, large masses of brilliance without definite form, "nebulous fluid," as Herschel used to call them. The spectroscope has shown indisputably that this view is correct, that there are such clouds of luminous gas, while photography later added the fact that there must also be great clouds of non-luminous material. Especially Barnard at Yerkes and Wolf at Heidelberg have greatly advanced our knowledge of these objects.

The dark nebulæ are unquestionably great clouds of "dust," and are visible only because they obscure the light of the stars behind them, thus causing the appearance of "black holes" or "dark lanes." Noteworthy examples of such occulting clouds are the "coal sack" in the southern Milky Way, shown on Plate VII to the left of the Southern Cross and the "Horse-head" Nebula in Orion, portrayed in Plate X. The whole region of the star Rho Ophiuchi seems to be teeming with many such dark lanes, all apparently emanating from the same centre, where, in the immediate vicinity of the bright star, the black nebulæ become luminous themselves,

as is plainly shown in Plate XI. The same holds here as well as in the Horse-head Nebula, Plate X; the obscuring cloud changes into a bright wisp of nebulosity when it approaches a bright star. No doubt the dust cloud is then shining by reflected light, or is, perhaps, incited by the powerful radiations from the very hot star.

As an illustration of the former supposition, Hertzsprung calculated the brightness such a nebula should have if it were shining by reflected light, and found that in the case of the Pleiades the nebulosity in which the brighter stars are imbedded is only 5 per cent. as brilliant per square inch as a sheet of white paper would be. Slipher then determined the spectrum and found it to be, as expected, of the type associated with reflected light. More recently, Hubble has thoroughly analyzed all the known "diffuse" nebulæ. He has shown that, with a few exceptions, the stars are physically associated with the nebulæ, and are their source of luminosity. Thus the "North America" Nebula (See Plate XII) may depend for its luminosity on Deneb, the very bright nearby star. The great nebula in Orion appears bright to us because of the abundance of bright stars imbedded in a vast mass of "black" material. To the naked eye this nebula appears as a hazy spot of light just under the three stars that form the "belt" of Orion; to the eye of the photographic camera, whose sensitivity increases with the

Photograph Mount Wilson Observatory

PLATE X

The Horse-head Nebula in Orion, near the star Zeta Orionis. It consists of a great mass of obscuring material illuminated at the edge by a bright star behind it. The multitude of faint stars in the upper half of the picture are situated at greater distances than the cloud; while the few stars seen in the lower part are all nearer than the cloud, and appear projected against it. None of the stars shown is visible to the naked eye.

time of exposure, the nebula appears to extend over almost the entire constellation.

There can be no reasonable doubt, then, that the dark nebulæ, as well as many of those of the Orion type—often called diffuse and gaseous nebulæ, are all cosmic dust clouds, shining only when illuminated by a neighboring star. When we call them clouds of dust, however, we must not confuse them with such dust clouds as we know on earth. From the probable value of the mass of the Orion nebula, it has been calculated that the mean density must be less than one millionth of a billionth of that of air under ordinary circumstances; that is to say, at most equal to the density resulting from expanding one cubic inch of atmospheric air over a volume of a cubic mile. On earth we should call this an extremely good vacuum. In the stretches of space this density is so great that a cloud of gas of such tenuity acts as a very effective screen, cutting off completely the light of the stars behind it.

According to the newest researches of Eddington, these nebulæ are only condensations in the "gas" that fills all space nearly uniformly. The density of this inter-stellar gas must be considerably lower still, probably not more one ten-thousandth part of that of such a nebula, or about equal to one ounce of matter distributed evenly over a space of twenty-five thousand million cubic miles. This does not seem excessive; nevertheless, if it is added up throughout the millions of light years at the dis-

posal of the astronomer, it amounts to a great deal. One cubic light year contains—or rather, one cubic light year of "empty" space "weighs"—about one septillion tons: a number with 24 ciphers. A thousand cubic light years weigh as much as the sun on this basis. This interstellar gas would be ionized by the ultra-violet light from all the stars. Thus, if it contained calcium, we would expect to find, in stellar spectra, absorption lines of calcium, which did not share the motion of the stars. Thus, an explanation is found for the strange phenomenon of the "stationary calcium lines," which have been the subject of much investigation by Hartmann at Göttingen, Plaskett at Victoria, and Struve at Yerkes. In fact, Struve has used the increasing strength of these lines as a measure of increasing absorption, and thus determined the distances of a number of stars.

Although nebulæ usually present too vague an appearance to allow of precise measurement of position, it has been found possible in two special cases to measure motion. One nebula in Taurus, called the "Crab" Nebula, is in the process of expanding rapidly, while another, the "Network" Nebula in Cygnus, consisting of two feathered wisps of nebulosity in the shape of an oval, is likewise increasing its dimensions. In spite of the uncertainty involved, it is tempting to reverse this process in our imagination and see if it is not possible that, some time, long ago, those nebulæ were caused by the bursting of a

Photograph Yerkes Observatory

PLATE XI

The region surrounding the star Rho Ophiuchi, showing extended irregular masses of obscuring clouds, an interstellar "fog" that hides from our view all the stars behind it, but which itself becomes luminous when excited by the radiation of a hot star near it.

new star. In the case of the crab nebula we actually have a record, though admittedly uncertain, of a new star that blazed forth at about the required time, which makes the above speculation seductively plausible.

To the measurement of radial velocities the ill-defined appearance of the nebulæ presents no obstacles; the lines in the spectrum are just as sharp as in a star, and many velocities in the line of sight have been measured at the Lick and Lowell Observatories. It has even been possible to measure the internal turbulent motion in the great nebula in Orion.

There is still a third type of nebulæ, the planetary nebulæ, so named because they are much sharper in outline than the others and present a disk somewhat similar in appearance to that of the planet Uranus. Practically all contain a faint star in or near the centre and often show shells or rings of light of different intensities. These central stars are all very hot, some fifty thousand degrees Fahrenheit at the surface, but there appears to be some evidence that they are rather small in size. The planetary nebulæ themselves are probably not very different in dimension, about 10,000 times larger in diameter than the orbit of the earth. Their masses are probably comparable to those of the heaviest stars, some 20 to 100 times that of the sun; but, even so, their density must be exceedingly small, in

fact not much larger than that which we found for the Orion Nebula.

The most puzzling feature of these planetary nebulæ and of some diffuse nebulæ concerns the character of their light. Analysis with the spectroscope showed a number of lines which could not be ascribed to chemical elements of terrestrial origin. Especially two strong and typical lines in the green, often identified with a hypothetical element "nebulium," provided a mystery difficult to solve. Very recently, however, even this secret was wrested from the nebulæ, representing the culmination of a long and arduous labor in which the foremost astronomers of the country took part. Under the persistent attack of Wright at Lick, the problem slowly neared solution, until only the exact identification of the green lines remained as the last stronghold to be conquered. And now, even this has capitulated; after a masterful summary of the problem by Russell, Bowen attacked it and solved it with the aid of modern physics. The green nebular light so long ascribed to an unknown substance, the mysterious nebulium, now takes its place among all other celestial radiances as the easily explained, and necessary consequence of the modern theories of light and of the constitution of the atom. By the time Bowen began his work it had become increasingly probable that the green light was due to ordinary terrestrial gases emitted under conditions peculiar enough to excite a gas, which is millions of times more rarefied than

Photograph Yerkes Observatory

PLATE XII

The North America Nebula in Cygnus, a large, diffuse nebula, near Deneb, the brightest star of the constellation. The light of the nebula may be a reflection of that of Deneb; its distance from us is probably around 600–700 light years.

our atmosphere and of itself intensely cold, into giving light. Physics knows of only two ways in which this can be done: by bombardment with high-speed electrical particles, or ultra-violet light, and in either case we are immediately referred back to hot stars. We must look for the solution of the mystery in the radiation sent out by the central star and in the peculiar conditions of the surrounding gas. To make a long story short, the solution lies in the extreme rarefication of the nebula. Even in the best vacuum we can produce in the laboratory there are enough molecules of gas left to cause each of them to collide several thousand times per second. If, now, the strong radiation caused by a very hot source of light has brought a gas particle into such a state that it could send out this green light a collision with another particle would destroy that peculiar condition. In the planetary nebula, on the other hand, matter is so tenuous that a particle may travel for weeks and over a distance equal to an astronomical unit, instead of a thousandth of an inch, before it collides with another. The peculiar state due to the radiation from the hot star is retained, the green light, so characteristic of the nebulæ, results, and the mystery is explained. The principal green lines, it is found, are emitted by oxygen, other lines in the spectrum of the nebulæ formerly ascribed to nebulium also, now appear caused by nitrogen, and we may thus say with

Russell that "nebulium has literally vanished into thin air."

Bowen's *coup* is the crowning achievement of a long series of investigations which have resulted in the shattering of one more romance of astronomy: the nebulæ have ceased to exist as such. They have been reduced to cosmic dust, have lost their independence, so to speak, and are shown up as shining merely under stimulation of stars. When the star is very hot, the nebula takes in the light and transforms it into radiance of its own liking, principally green light; when the star is comparatively cold, however, the nebula can do no more than reflect the light. When there is no bright star near, the nebula remains "without form and void," and acts as a curtain, obscuring everything behind it: "Darkness is upon the face of the deep." Once more the stars have risen to the position of being the only independent denizens of the cosmos, the only ones that shine with a glory of their own.

Chapter XIII

STELLAR EVOLUTION

> "Thousands of human generations, all as noisy as our own, have been swallowed up of Time, and there remains no wreck of them any more; and Arcturus, and Orion, and Sirius are still shining in their courses clear and young as when the Shepherds first noted them."
>
> —CARLYLE.

How is a star born? How long does it live? How and why does it die? These and other questions have been perplexing astronomers for the past few decades, have been the driving power of astrophysics. It is only during the past few decades, since the advent of photography and of the spectroscope, that we have known enough to ask such questions intelligently. It is only since then that we have really begun to consider the stars otherwise than as mere specks of light, that we have become interested in their physical constitution.

In a way it should be simple for the astronomer to write the biography of a star—the stars really write their own life histories. That is to say, the data are already there; all the astronomer needs

to do is to heed the writing in the sky, traced in words of flame and fire, and decipher the code of these celestial autobiographies. Parts of them are written in infinitesimal characters, the language of the atoms and electrons. These are the easiest to interpret, for the recent atomic theories have supplied us with an excellent Rosetta stone, and we have been able to translate no small part of them. Especially the epoch-making work of Eddington has enabled us to penetrate deeply into the interior of the stars, into the innermost of the cosmic crucibles. Thus far, however, the Ten Commandments which govern the life-course of a star are not yet fully understood, though we have reason to believe that the tablet on which for trillions of years past the stars themselves have been chiseling this decalogue has been brought to light, largely through the efforts of Lockyer, Hertzsprung, Russell, Jeans, and Eddington. The alphabet employed in these stellar cuneiforms has not yet been established, and only one of the commandments seems to have been fully translated: "Thou shalt not be heavy." Eddington has shown that stars much heavier than the sun are extremely unstable and will explode at the slightest provocation.

That astronomy with all the means at its disposal has not yet progressed beyond this point must not seem surprising. Indeed, the task of interpreting correctly the evidence of stellar evolution is much more formidable than it appears. Here on earth,

where the average lifetime of a single individual falls considerably short of a century, and where the average interval between generations is about thirty years, we are in possession of records of the history of man for a period of thousands of years. But for the history of the stellar universe we have records of not more than forty years, while the average life of a star must be at least a quadrillion years, a number with 15 ciphers. On the earth, even the suggestion that evolution takes place seems to meet with at least a few objections; with the stars, although astronomers may hold different opinions as to the how and why of stellar evolution, they all admit its necessity.

When we say that our records are only a few decades old, we mean those records that can be used as evidence in the search for traces of stellar evolution. Although the stars have been observed, wondered at, and thought about from time immemorial, man's knowledge never reached far beyond the mere fact that they *existed*. Their physical constitution remained behind a closed and sealed door until, under the combined attack of photography and spectroscopy, the seals were broken. Once the door was unlocked a glimpse was caught of a treasure so vast that its full importance is not yet realized.

We may say that we have, at most, forty years of spectroscopic research behind us, and what is forty years compared with the time scale of the

astronomer, to whom a million years is "as but a day"? I believe it was Simon Newcomb who illustrated the difficulty of the problem by the following comparison: imagine a person endowed with the keenest powers of reasoning and in possession of the finest and most accurate instruments we have as yet produced, a person, furthermore, who has neither seen nor heard of a pendulum. Imagine this person placed in a completely darkened room, where numerous pendulums are swinging noiselessly. Illuminate this laboratory for one single instant by a flash of lightning. Then demand from the observer that he explain the law that governs the motion of a pendulum. And yet, his task is child's play compared with the stupendous problem of the astronomer who has to derive a theory of stellar evolution, for the duration of the electric flash against that of the swing of a pendulum is, comparatively speaking, millions of times longer than forty years in the life of a star.

With such an immense task before us, it is well to assemble what we really know, before we venture forth on the perilous undertaking of theorizing. In gathering our evidence we must also be careful to select with the least possible prejudice, paying more attention to facts than to appearances. For things are not what they seem. The stars, as they appear to us in the sky, are not at all representative of the stars as a whole, and any theory derived solely from the stars we can see without the aid of a telescope

might be very materially wrong when applied to the stars as we find them in space. We have seen before how much the stars may differ in luminosity, how the giants of yellow color may outshine the dwarfs by more than a thousand to one, and how the giants of all types exceed the sun more than a hundred times in brilliance. Of all the stars visible to the naked eye, some 6,000 in number, at least 4,000 may be classed as giants; of the remainder, probably less than 200 are inferior to the sun in luminosity. If, on the other hand, we take a sample of 6,000 thoroughly representative stars in space, we should find that more than 75 per cent. are fainter, intrinsically, than the sun, while the giants contribute no more than a miserable 2 or 3 per cent. The stars visible to the naked eye, therefore, prove to be exceptions rather than typical specimens, which circumstance adds another difficulty to our already involved problem: the naked eye stars lend themselves especially to accurate and detailed observations by their greater brightness, and now we find that the larger part of our best observations has been made on exceptional cases. Persistent attacks and statistical evaluation of the material, avoiding as much as possible the selection introduced by the observations, have ultimately resulted in the establishing of at least a few facts.

The principal one among these is Hertzsprung's discovery that the vast majority of the stars arrange themselves very neatly in a sequence, running from

the very luminous, and very hot, blue and white stars down to the insignificant and obscure red dwarfs. At the upper end of this series stand the redoubtable Orion stars, 35,000 degrees Fahrenheit in temperature, bluish-white in color, and surpassing the sun between 100 and 10,000 times in light-giving power. Halfway down the line is our sun, not more than 10,000 degrees in temperature, while at the lower end we find millions of faint red dwarfs, 5,000 degrees or less in temperature, and between 100 and 10,000 times fainter than the sun. Hertzsprung immediately suggested that this sequence was the main branch of stellar evolution; the yellow and red giant stars which did not conform to it were, for the time being, treated as exceptions.

It was Russell who, a few years later, first proposed a very attractive theory of evolution, taking into account the above-mentioned facts which he had come to independently of Hertzsprung. In Russell's theory the red giant stars of the type of Betelgeuse and Antares head the list and represent the very first stages of stellar evolution. As such a star grows older, it contracts and becomes hotter, thus going through various metamorphoses, finally arriving at the hottest and most luminous stage, that of a blue-white giant. It has now reached the pinnacle of its fame, and shines without rival among the stars; from now on it is doomed to grow cooler and fade, although still continuing to contract. It passes through the stage now occupied by the sun

and ultimately reaches that of the red dwarfs, which we thus see as the sad remains of the celestial fire, nothing but a lingering memory of the giant stars of the Orion type, once so proud and powerful that their light messages penetrated to the utmost depths of space, but now scarcely able to flicker to their immediate surroundings their last *Morituri te salutamus*.

For a while Russell's theory, though not entirely unchallenged, remained the only workable one. As time went on, however, new data accumulated, and data seemingly incompatible with the theory. Foremost among these were the "white dwarfs," stars of enormous densities, whose existence had been indicated for some time but was definitely proved by Eddington. In his researches on the internal constitution of the stars Eddington first came to the remarkable conclusion that, paradoxically enough, as stars grow heavier, things on their surface begin to "weigh" less and less. A new force, the pressure of radiation directed outward and resulting from the enormous flow of energy emanating from the interior of a star, arrives on the scene. Since "light," according to relativity, has "weight," a stream of light rays exerts a pressure upon things material, and in very heavy and very luminous stars this pressure of light may even exceed the force of gravitation, and consequently such very massive stars may explode without warning. Conclusive proof of the theory lies in the fact that we do not

know of one single star more than 100 times heavier than the sun.

During the course of his subsequent investigations Eddington has indicated that the interior of a star will practically always behave as a "perfect gas." The physicist understands by a perfect gas a gas in a state of such extreme tenuity that the simplest gas laws are accurately obeyed. Under ordinary circumstances there are always slight deviations from these simple laws, deviations which grow larger and larger as the density of the gas increases. For a density ten times greater than that of atmospheric air such deviations are already quite marked, and we had always, rather naturally, supposed that in stars of the density of the sun, more than one thousand times denser than our air, these deviations would be enormous. On the contrary, the deviations are far less, almost negligible, and for no other reason than that the temperature in the interior of a star is so excessively high, several millions of degrees, that it has changed the gases to such an extent that they will again behave as a perfect gas. The effect of temperature on a gas is to set it in violent motion, not only the particles of the gas itself, but even the electrons inside the individual particles. When the temperature becomes sufficiently high, the electrons are shot off, the atoms are "stripped," and the size of the smallest particles in the gas are reduced so considerably that, although they may be condensed to weighing one thousand times more

per cubic inch than before, there is, relatively speaking, so much more room for the smaller particles to move that they behave more nearly like a perfect gas than ever before. Continuing his argument in the same direction, Eddington finally explained the existence of white dwarfs, stars with a density 25,000, 100,000, perhaps as much as 1,000,000 times greater than water.

As an alternative to Eddington's perfect gases, Jeans has recently advanced a singularly attractive theory based upon the idea that the stars really behave as liquids. Finding that, under the conditions possible in the inside of a star, it must behave either as a perfect gas or as a liquid, Jeans then indicates that when a star is in the "perfect gas" stage it is very unstable, and will soon try to become a stabler configuration, a liquid. Again, Jeans obtains his arguments from the modern theories of the atom: it is owing to the wishes of the individual atoms and electrons that a star behaves as it does. Apart from this majority rule in its interior, however, a star has not many ways to go. The few possibilities are a direct outcome of a race between the diameter of the star and the size of the atoms, the stripping of the atoms really being due to a change in temperature, which accompanies any change in diameter. In Jeans's happy figure of expression, a "case of the tortoise and the hare." "If the stellar diameter is the tortoise, the atomic diameter is the hare; its progress is by spurts and

rests alternately. The spurts of the hare do not save it from ultimate defeat, but they result in its being alternately in front of and behind the tortoise." As in Eddington's theory, the ultimate stage is that of the white dwarfs, where the atoms are completely stripped of all their electrons. The hare has jumped for the last time, and when next the tortoise catches up with it they become both caught in a trap from which no escape is possible. On previous occasions, whenever the atoms became so closely packed that they had no elbow room, it was always possible to strip the atom some more, to reduce its size again, and make room. In the white-dwarf stage the atom is stripped to the core, it is the final stage, and the star will remain in it until the end of its days.

At the same time that they developed their theories on the interior of a star, both Jeans and Eddington approached the question of what keeps the stars going, how they replenish the incessant stream of light and energy they are pouring out into empty space. This, naturally, is intimately connected with the problem of stellar evolution, since a complete answer as to where the energy comes from will provide us with a time scale for evolution. Since the whole process goes on in the interior of a star, we cannot be certain but only conjecture what takes place. According to Jeans and Eddington, *matter* is being annihilated on a large scale. That this is possible is a new idea, introduced by rela-

tivity, which claims that matter and energy are, after all, merely different manifestations of one and the same thing, and may well be transformed one into the other. Also according to relativity, a small amount of matter will go a long way. Take, for example, the changing of hydrogen into helium. If we start out with one pound of hydrogen, we do not get our full pound of helium. We find that we are short one eighth of an ounce, and it is this eighth of an ounce of the life blood of matter that has been transformed into a prodigious amount of energy, light, heat, or radiation. It would suffice to heat one million tons of water from freezing to boiling. For this reason, hydrogen has often been called matter unborn; it is not matter in the ordinary sense of the word, since it carries this excess weight of eight tenths of one per cent. which is not matter. And, according to the laws of the universe, this small percentage of explosive contents is cosmically intoxicating. Once, however, the catastrophe has taken place, that is, from helium onward, matter behaves perfectly normally: after it has shot the rapids of this Niagara of matter, it flows on quietly in regular channels and creates no further disturbance.

According to Eddington and Jeans, the actual process that goes on in the inside of a star need not be that of converting hydrogen into helium; some similar action would do equally well. It does appear reasonably certain, however, that the source

of stellar energy must be sought in the annihilation of matter on a large scale, since this is the only process known at present that will liberate an amount of energy sufficient for the maintenance of stellar radiation for trillions and quadrillions of years.

From all the facts at present at our disposal, we may confidently surmise that the age of the stars must at least be of the order of magnitude of a trillion years. Our sun, not yet an old star, although undoubtedly its tumultuous youth is past, is probably not less than several trillion years old; a star of the red-dwarf type may well be a quadrillion years old.

No matter which way the course of stellar evolution runs, no matter which way the star chooses to go, red dwarf of low temperature, or white dwarf of high temperature and exceedingly great density, the end is inevitable. The star's career must come to an end, and the curtain is lowered at the close of the last act of the celestial drama. The ghost-like body of the extinguished star may continue to roam through space, it may wander on for trillions of years to come as a celestial vagrant—as a star it is no more, its tale is told, its glory dissolved. In due time it may be gathered in and thrown on the scrap heap of the universe, but who knows that some day it may not be thrown into some cosmic crucible, together with a score of other dead bodies, be rejuvenated, and arise as a Phenix from its ashes?

Chapter XIV

THE MILKY WAY SYSTEM

> "When the astronomer says that the light from a star takes one hundred years to reach us, the lie is too great to be artistic."
>
> —SHAW.

ALTHOUGH following the general scientific tendency toward diversity and complexity astronomy never loses sight of the unity of creation. In our detailed description of the different kinds of objects in the universe, their dimensions and their velocities, this unity may have become obscured. Yet the stars are not distributed at random, nor do they wander aimlessly through the shelterless deserts of astronomical space; the variable stars, the clusters, and nebulæ all play their unobtrusive parts in making up that great organization known as the Milky Way system.

In the heavens the Milky Way appears to us as that faint, hazy, but broad band of light encircling the whole sky, a band of light so faint, indeed, that moonlight causes it to disappear almost completely. The presence of a small amount of artificial light is enough to subdue it perceptibly and the city

dweller rarely gets a good view of the Milky Way. If, however, we were to go into the solitude of the desert, or high into the mountains, preferably in southern latitudes, far from the disturbing illumination of civilization and above the haze and dust of the lower regions of sea level, we should behold an entirely different spectacle. A great arch of wondrous beauty stretches across the vault of heaven, its vague windings sometimes reaching as high as the zenith, and at times of such resplendence as to cast a shadow. If we could but remove the earth, or place ourselves in such a position in space that the whole sky would be visible, the complete Milky Way would be seen as a great circle making the entire circuit of the sky.

When we examine the Milky Way in more detail, we notice that its boundaries are not well defined, and that the whole broad and faint band of light varies in width, as well as in brilliance. In the constellations Auriga, Monoceros, Orion, and Argo it is very broad and faint, while it is very bright in the region of the Southern Cross, and reaches its greatest splendor in Scorpio and Sagittarius. In the constellation Cygnus the Milky Way divides in two, the main stream continuing down through Aquila into Sagittarius, while the secondary branch extends southwestward into Ophiuchus and gradually dies out. In many places, especially in Sagittarius, the light seems to condense into star clouds and, as a contrast against these, there appear black

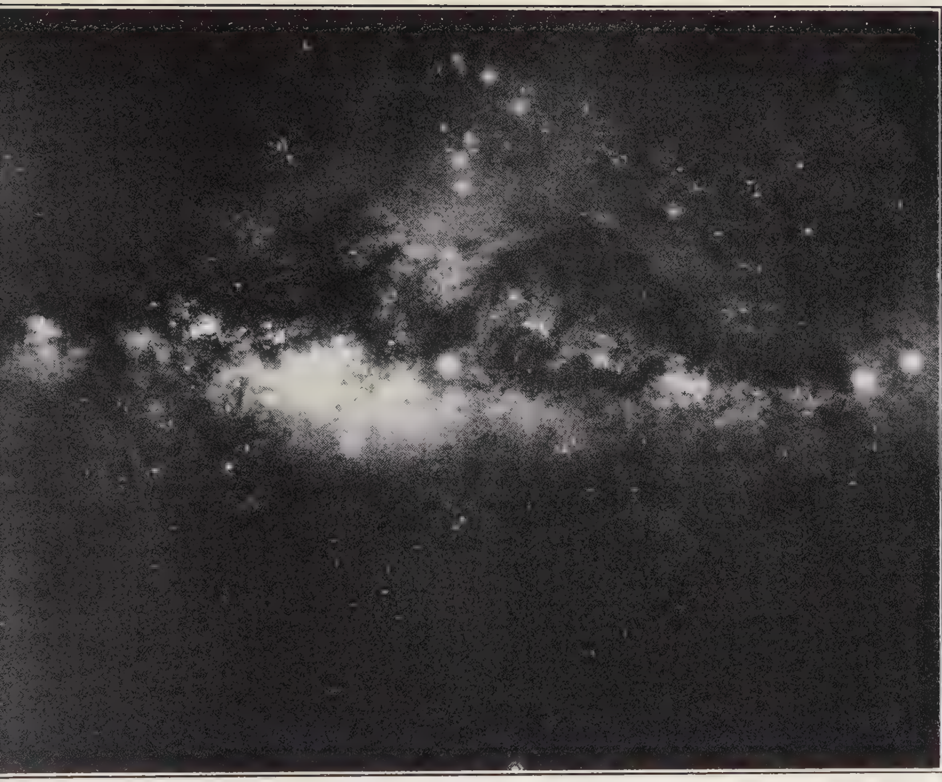


PLATE XIII

A portion of the Milky Way, extending from Aquila to Centaurus, and containing the great star clouds in Sagittarius. The centre of our Milky Way system is probably situated in the direction represented by the middle of the plate, but a large number of the stars belonging to this central condensation of our system seem to be obscured by dark clouds. The two bright stars on the right, near the edge of the plate, are Alpha (left) and Beta Centauri. In the centre is Lambda Scorpii, while the constellation Scorpius continues from there upward, including the group of bright stars near the top. The bright star near the bottom of the plate is Alpha Pavonis. (The plate is a composite photograph obtained by fitting together prints made from thirteen different negatives. The lines produced at the junction of the separate prints show faintly. The original negatives were all taken at the Arequipa station of the Harvard Observatory, with a lens of $1\frac{1}{2}$-inch aperture.)

spots, seemingly void of stars and doubtless due to huge masses of obscuring material. The main features of such star clouds are well shown on the plate of the Milky Way in Sagittarius and Scorpio; the "coal sack," shown in the illustration of the Southern Cross, is a good example of the obscuring clouds.

If a telescope is pointed toward any portion of the Milky Way, a multitude of faint stars immediately spring into view; if we sweep the whole domain of the Milky Way with even a small telescope, this army of stars grows into tens and hundreds of thousands. On long-exposure photographs of Bailey, Barnard, and others, hundreds of thousands of stars are sometimes shown on one plate; we possess one plate at Harvard on which no less than half a million stars may be counted. From the latest researches of Van Rhijn and Seares it is estimated that the total number of stars in the Milky Way that could be photographed with the 100-inch reflector at Mount Wilson is probably of the order of two or three billion.

When contemplating this immense structure around us, the question arises as to what interpretation we shall put on the data. It seems rather absurd to imagine that the sun is in the centre of an enormous ring of star clouds, and much more reasonable to suppose that the whole structure of the Milky Way system is shaped like a watch filled with stars throughout, and with the sun situated

not too far from the central plane, although not exactly in the centre. William Herschel, the pioneer in this branch of astronomy, already held this latter view, and although, with the data available in his day, it was impossible to arrive at anything but the crudest approximation, he foresaw the time when this problem could be solved in its principal aspects. In his words, the ultimate goal of astronomy consisted in the determination of the distance of every star in the universe; once this was done, the vast structure of the Milky Way system would reveal itself. We have intimated before how impossible such an ideal solution of Herschel is, even in our days: our best methods of triangulation do not reach beyond 1,000 light years, while the distances of the remotest portions of the Milky Way may number 30,000 to 50,000 light years. Again we have to resort to statistical means, and in doing so, we incidentally enlarge Herschel's definition of the 'goal of astronomy,' to take in, not only the distances of the stars, but also their luminosities, their sizes, their masses, and their motions; in short, we want a picture of the living and moving universe. The difficulties attached to a problem of such scope seem well-nigh insuperable.

To mention but one instance: looking upon the photograph of the Southern Cross and its surroundings, we note the fact that the nearest known of all stars, Proxima Centauri, is so faint that it is indiscernible among the confused mass of other faint

objects, and can be found only with difficulty on the original negative. On the other hand, the brightest star near the centre of the plate, Alpha Crucis, is so far away that its distance has not yet been measured with any degree of certainty. On the plate it appears more than 10,000 times as bright as Proxima; in reality, its luminosity must be more than 4,000,000 times greater than that of our nearest neighbor in space. Apparent brightness, therefore, is but a poor criterion of nearness, and for the host of faint stars in the Milky Way, where we lack all information concerning color or motion, we must resort to wholesale statistical devices in order to arrive at even an approximate first solution.

The best and most comprehensive determination that has thus far been made is that of Kapteyn who, practically single-handed, inaugurated the modern era of statistical research and had the great happiness of seeing his life-long labors come to fulfillment in this, his picture of the Milky Way system. According to his results, this "Kapteyn Universe," as it is commonly called, is an immense conglomeration of stars, flattened in shape and somewhat resembling a bun, or a watch. The "dial" of the watch is five times larger in diameter than the thickness, although there really are no sharp boundaries, but merely a falling off in star density toward the edges. As a first approximation, the sun had to be assumed near the centre of this system, and it is found that the star density—that is, the number of

stars per cubic million light years—decreases from the centre outward. Near the sun a cube $100 \times 100 \times 100$ light years, or equal to 1,000,000 cubic light years, contains on the average about 1,500 stars, but at a distance of 10,000 light years in any direction in the plane of the Milky Way this number has already been reduced to 150, while at a distance of 30,000 light years we find no more than 15 stars per cubic million light years, only 1 per cent. of the star density near the sun. Since the "watch" of the Milky Way system is rather thin, the falling off in numbers of stars in the direction of the smallest thickness, that is in the direction of the poles of the Milky Way, is much more rapid than in the plane. Instead of 10,000 light years, we now do not have to go more than 2,000 to find the number of stars per cubic million light years reduced to 150, or 6,000 light years to find that number as low as 15. This state of affairs explains why we see the Milky Way in the sky as a luminous band, containing far more stars than the regions near the poles of this great circle. It is simply that in the direction of the Milky Way plane we see through five times as much distance, and a great many more stars combine their light to make up the total glow, than in the direction of the poles.

Kapteyn also determined the relative numbers of stars of different intrinsic brightness as an incidental by-product of his researches on the structure of the Milky Way system. He found that for every

1,000,000 stars of the luminosity of the sun, space contains 200,000 stars 10 times brighter, 16,000 stars 100 times brighter, 450 stars 1,000 times brighter, and only 5 stars 10,000 times more luminous than the sun. Stars such as Rigel, Canopus, and Deneb are exceedingly scarce, therefore, and the only reason that we see a considerable number of them even with the naked eye is that, through their great luminosity, they are visible at far greater distances and over a far greater portion of space than their less luminous brothers. For stars intrinsically fainter than the sun the numbers augment rapidly, stars 10 times fainter than the sun being represented by 1,800,000 in the above series, stars 100 times fainter by at least 2,000,000. For stars still fainter our present knowledge is so sketchy that it is difficult to say how large their number is, although it seems indicated by the work of Hertzsprung and others that they are far more numerous than was previously believed.

Another outcome of Kapteyn's great investigation is concerned with the velocities of the stars. If, again speaking in first approximation, they are assumed to be at random, in size as well as in direction, the whole Milky Way system may well be likened to a gas in which the individual molecules representing the stars are in constant agitation. We have seen, however, that in the vicinity of the sun the star density is such that an analogous picture may be formed by taking a number of billiard balls

and placing them 3,000 miles apart on the average. In the outer portions of the Milky Way the star density is so small that we should have to place these billiard balls 10,000 to 20,000 miles apart, and if such a galaxy is compared with a gas, it cannot be with a gas under ordinary conditions, but with a vacuum. In fact, similar conditions would not exist in a gas until we had rarefied it to such an extent that it corresponded to a cubic inch of air spread out over one thousand cubic miles or more. Collisions which form the basis of all theories of gases must be exceedingly rare occurrences under such conditions: precisely what we have found to hold for the stars. If, reasoning further on the path of this gas theory, we calculate the velocities acquired by the stars under the gravitational attraction of the whole Milky Way system, or the *Galactic system* as it is often called, we find that their velocities should all be less than sixty miles per second. This leads to the conclusion that all stars moving faster than this limit will ultimately escape from the Galactic system, and in all probability they must have come from elsewhere originally: they are interlopers. On the other hand, it appears that the motions of these interlopers are, on the whole, remarkably parallel to the plane of the Milky Way, and seem to become more so as the speed increases. The plane of the Galaxy thus seems to have some essential connection with these stars, which could not be the case if they really came from

the outside and were not members of the Milky Way system. The problem has not yet been settled and will probably require a great deal more data before a satisfactory solution can be reached.

Kapteyn's ideas concerning the structure of the Galactic system were admittedly only rough and approximative: the few years that have elapsed since the completion of his work have indicated that probably the real structure is different and designed on a vastly larger scale. As a matter of fact, Shapley has shown that the Kapteyn Universe is little more than the *local cluster,* the group of stars surrounding the sun; this group itself is considerably off centre in the much more extended Galactic system. This centre he has estimated to lie at a distance of some 25,000 light years in the direction of the great star clouds in Sagittarius, and coincides with the centre found for the system of globular clusters and for that of the planetary nebulæ. In addition to this, the region of Sagittarius is very rich in "new" stars, and contains enormous numbers of variable stars. Evidence is rapidly accumulating tending to show that these great star clouds in Sagittarius are really so immense in size that they alone may well contain several billion stars. The greater Galactic system, of which these clouds form the centre, is probably as much as 300,000 light years in diameter, and still shaped like a watch, although considerably flatter than Kapteyn's system.

The great mass concentrated in this region will

then act similarly to the sun in our planetary system, and will force the other stars to revolve around it. Linblad and Oort have investigated this matter and found that there is some evidence to show that the sun and all the stars in its vicinity are rotating around this centre with a speed of 180 miles per second, which, if they kept up this speed, would make them complete one turn in about 200 million years. The local cluster may then be likened to a swarm of bees: the sun, belonging to the swarm is actuated by a velocity of 12 miles per second with respect to the average member of the swarm, while the swarm as a whole is revolving around the hypothetical centre of the Galaxy with a speed of 180 miles per second.

Vast as the framework is which we have designed and upon which we have built our comprehension of the Galactic system, it does not represent the sum total of our knowledge. Our telescopes have now revealed many objects that cannot be placed within the confines of that Milky Way system, while our minds had already pondered on their existence. From the Galaxy, of which our own sun is but an insignificant constituent, we pass on again into empty space toward a still greater conception of the material universe.

Chapter XV

ISLAND UNIVERSES

"The distance is nothing, it is only the first step that counts."

—MME. DU DEFFAND.

INASMUCH as universe means ALL, it is perhaps difficult to understand its use in the plural. By a change of meaning, which is as intelligible as it is illogical, universe to the astronomer is now limited to meaning all that was once thought to exist, instead of what really exists. Astronomical advance during the past few decades has been so rapid that astronomers find themselves hampered by the inadequacy of their language. New concepts quickly supersede older ones, new words have to be coined or older meanings changed. The Galactic system, once thought to be the whole universe, has been found vast beyond the wildest dreams, but of no avail; even its size of 300,000 light years is now shown as insufficient to include any but the smallest fraction of the real cosmos. Our conception of the material cosmos to-day is much broader; we see the abysmal chasms of space strewn with countless

"island universes," vast conglomerations of matter far beyond the confines of the Milky Way, scattered at distances of millions and perhaps billions of light years.

Long before telescopic observations warranted it, the Swedish philosopher Swedenborg and the English scholar Thomas Wright speculated upon the existence of such external stellar systems. In Germany Kant pursued this, but it was not until William Herschel's researches that the idea of island universes began to take on definite shape. The era of real observational evidence was inaugurated in 1845 when Lord Rosse discovered that a nebula in the constellation Canes Venatici appeared to be of a spiral shape. This most unusual and unprecedented discovery was doubted at first, but, as telescopes became more powerful, and especially as photography was introduced in astronomy, Rosse's discovery was established beyond doubt. The great nebula in Andromeda, one of the very few visible to the unaided eye, proved to be a spiral, likewise two nebulæ in the Big Dipper and a large nebulous structure in Triangulum. With the aid of the photographic plate spiral after spiral was discovered, and now they form a well-established and very numerous class of celestial objects. In some parts of the sky, notably in the constellations Virgo and Coma Berenices, many hundreds of such objects may be seen on a single photographic plate; in some very localized areas the spiral nebulæ may even be

more numerous than the stars. The total number of objects of this type that can be photographed with the 100-inch reflector is estimated at several million.

For some time after their discovery, astronomers speculated about the nature of these nebulous objects. Were they gaseous, like the real nebulæ such as the Orion nebula, or were they great aggregations of stars, only appearing nebulous because of their tremendous distance from us? The spectroscope soon put an end to this controversy when it showed that the light of these nebulæ does not resemble that of the real gaseous nebulæ. The work of Slipher, especially, has established beyond doubt the fact that the spiral nebulæ are aggregations of stars, since their spectra are roughly similar to that of the sun: a band of light, crossed by numerous dark lines indicating the presence of many familiar chemical elements, such as iron and calcium. Such spectra could only be produced by a large number of stars composed of the same materials as those known in our universe. When reflecting upon this observation we may well marvel at the power of spectroscopic methods: long before we knew anything about the distance of these spirals, long before we could distinguish the individual stars in them, the spectroscope had proved to us that the behavior of atoms and electrons in these far-distant structures was the same as in the stars and on earth. We might almost be tempted to say that at these

infinite distances we can study only the infinitely small.

Another outcome of the spectroscopic observations is the indication it affords concerning the velocities of the spiral nebulæ. If we can take measured differences between the light emitted by these spirals and that produced in our laboratory as attributable to their velocity, we find that they all have high speeds. The great spiral in Andromeda is probably approaching us with a speed of 200 miles per second, while the other spirals, with only few exceptions, are receding from us, some as fast as 1,000 miles per second.

The next question to be decided was: how far away are they? Since their apparent dimensions can be observed, this would involve also asking: how large are they? Placing them at moderate distances would make them over-sized star clusters, so to speak, while distances of a million light years or more would make them comparable to our Galactic system in size. For a while astronomical opinion was divided, as no definite evidence in favor of either supposition was available. The first fairly certain evidence came from the behavior of the new stars that had been observed to flash up in spirals from time to time. In the Galactic system such outbursts usually result in a "new" star which, at the time of its greatest brilliance, surpasses the sun more than ten thousand times in luminosity. If the reasonable assumption may be made that the

new stars in spiral nebulæ are about as bright, intrinsically, as those in the Galactic system, we merely have to determine the apparent brightness of the new stars in spiral nebulæ and we can calculate their distance. In this way, Lundmark and Curtis reached the conclusion that even the nearest of spirals must be about one million light years away.

About the same time, however, the opponents of such tremendous distances were greatly fortified in their opinions by the measures made by Van Maanen at Mt. Wilson, on the internal motions in the spirals. Van Maanen's conclusion was that these nebulæ were in rapid rotation, some of them making one complete turn in as short a time as 50,000 years. For an object so vast as a spiral nebula this is indeed incredibly short, altogether incompatible with the great distances derived by Lundmark. Suppose, e. g., that Lundmark's distance of 1,000,000 light years for the Andromeda nebula were correct, then its linear size must be about 50,000 light years. Suppose also that such a structure were rotating in as short a time as 50,000 years; then a particle near its outer boundary would, in 50,000 years, describe a circle with a diameter of 50,000 light years, or rather, the particle would complete a path more than 150,000 light years long in that time. Thus, it would travel more than 3 light years per year. In other words: *it would go faster than light.* Here we have

reached an absurdity, an impossibility, according to our present way of thinking. The doctrine of relativity postulates that the speed of light is the greatest possible, and that no material particle can travel with such a speed, let alone surpass it. Whatever relativity decrees is the constitution of the universe, it allows of no violations of its laws, of no exceptions to it. Either we have to abandon our theory of great distances or disbelieve the rapid rotation of spirals. Since the large distances were based upon indirect evidence of somewhat uncertain value, astronomical opinion on the whole seemed to favor Van Maanen's views, though Curtis and Lundmark dissented. The pendulum of progress again swung from island universes to star clusters, and the Galactic system once more rose supreme.

The island-universe theory suffered no more than a temporary relapse, however, as again the pendulum swung forward—definitely, this time, as we now think. Hubble, at Mount Wilson, discovered a number of variable stars in the Andromeda nebula, variable stars of the Cepheid type. As we have seen before, such variables constitute a beacon whose candlepower is accurately known, and thus the distance of the Andromeda nebula may be found. Again, the distance proved to be nearly one million light-years, a complete vindication of Lundmark's earlier work. Hubble's evidence is of such fundamental importance in the problem of

Photographs Mount Wilson Observatory

PLATE XIV

Above: The Sombrero Nebula, an island universe in a very early stage of development. It is situated in the constellation Virgo, and probably not less than 10,000,000 light years distant.

Below: Left: A close group of spiral nebulæ in Pegasus, containing three large spirals, all of about the same "age," and one, much "younger," elliptical nebula which, in all probability, is much farther away. Right: A twin universe in the constellation Virgo, just at the point of developing into two spiral nebulæ.

stellar distances, and is at present believed to be of such great weight, that his results are now universally accepted. Island universes it must be, and the rotation, previously given credence, must go.

The best known of all island universes is undoubtedly the Andromeda nebula, the only one visible to the naked eye in our latitudes. It is a great, spiral-shaped structure about fifty thousand light years in diameter, but rather flattened in one direction, not unlike the Galactic system. It is almost one million light years distant, and contains millions and possibly billions of stars, the vast majority being too faint to be seen individually, although actually they may greatly surpass the sun in luminosity. In fact, our sun, if removed to such an immense distance, would be of the twenty-seventh magnitude, more than one hundred times fainter than the faintest star within reach of our most powerful telescopes of to-day. In 1885 a new star blazed forth near the centre of the Andromeda nebula, and reached the seventh apparent magnitude. It is generally supposed that the star was really connected with the nebula, and thus also situated at a distance of 1,000,000 light years: in that case, during the time of its maximum brightness, it must have been 100,000,000 times as luminous as our sun, one tenth as bright as the whole Andromeda universe. During the few days of its maximum splendor, it reigned supreme in the cosmos; it was the brightest star we have ever observed. It was

also the most wasteful, for at that time it was so prodigal in radiating away its light and energy that, according to the theory of relativity, it was losing mass at the rate of more than one hundred million million tons per second. In addition to this phenomenally brilliant nova, about eighty-five others have been observed to date. These do, indeed, justify Lundmark's original supposition that they are comparable to those in the Galactic system, since these distant novæ, too, reach a maximum brightness which is, on the average, about 10,000 times that of the sun. In addition to the novæ, scores of variable stars are known in the Andromeda nebula, discovered by Hubble at Mount Wilson. Recently there were found at Harvard two bright variable stars which are, in all probability, connected with the spiral. In that case their light varies between the limits of 25,000 and 100,000 times brighter than the sun.

Although the Andromeda nebula is the nearest of all spirals, it is not the nearest island universe. Three others are known at present: a faint, nebulous looking object, known under the technical name of N. G. C. 6822, and the two Magellanic Clouds, which we have had occasion to mention already. They are both well visible to the naked eye in Southern latitudes, the Large Cloud being about seven degrees in diameter, the Small Cloud about three and one half. To the naked eye they look almost as if they were patches torn off the Milky Way.

It was from them that our first clue came concerning the luminosity of Cepheid variable stars, and they were the first objects whose distance was determined from the Cepheids, by Hertzsprung, who found a value of 30,000 light years. Using much more up-to-date material, Shapley has recently arrived at a value of 100,000 light years for their distance. Since these clouds are seen at a considerable angular distance from the great circle of the Milky Way in the sky, such a distance places them well outside the Galactic system. They are island universes in miniature, being no more than 7,000 and 14,000 light years in size. In them we find all the different types of objects with which we are so familiar in our own Milky Way system: stars, variables, gaseous nebulæ, globular clusters, and we might well consider them as dwarf galaxies. Shapley has also found that the largest of the nebulæ in the Magellanic Clouds is of such enormous dimensions that, if it were placed at the same distance as the stars in Orion, it would fill the entire constellation and appear as bright as Venus. It contains in its centre a variable star that alone is more than 100,000 times brighter than the sun. Thus far only one new star has been discovered in the Clouds; it reached a maximum brightness at least 10,000 times greater than that of the sun, in full accord with the behavior of novæ in other universes.

At the southern station of the Lick Observatory the velocities in the line of sight of several gaseous

nebulæ in the Clouds have been measured, and it has been found that the Large Cloud is receding from us at a speed of 170 miles per second, the Small Cloud with a speed of 100 miles per second. From their proximity in the sky, their similarity in structure, and from the remarkable progression in the velocities of the nebulæ situated in different parts of the Clouds, Hertzsprung has tentatively reached the conclusion that they may form a twin system, which, as a whole, is animated by a velocity of 400 miles per second. This speed is probably great enough to overcome the attraction of the Milky Way system, and allow the Magellanic Clouds to escape from our vicinity. If, however, the total mass of the Galactic system is much greater than we now have reason to suppose, it becomes barely possible that the Galactic system will prove the stronger of the two and force the Magellanic Clouds to circle around us, and form a kind of satellite universe to ours.

During the past few decades a large amount of material on spiral nebulæ and island universes in general has been painstakingly accumulated by Curtis at the Lick Observatory, Wolf at Heidelberg, Reynolds at Helwan, Egypt, and by Hubble at Mount Wilson, the last of whom, having the 100-inch reflector at his disposal, could penetrate much deeper into space than his predecessors. As a result, a great variety of island universes have been found and when an attempt is made to arrange

Photograph Mount Wilson Observatory

PLATE XV

The great spiral nebula in the Big Dipper, an island universe of medium age still in the process of unwinding its spiral arms. The distance from us is probably not far from 5,000,000 light years. None of the stars shown in the photograph is visible to the naked eye.

these in different groups, according to their appearance, as has been done especially by Wolf, Hubble, and Lundmark, the strange fact appears that such an arrangement is nearly identical with that proposed by Jeans in England from purely theoretical considerations. In such a case we may feel reasonably confident that Jeans's attractive conception of the origin and development of spiral nebulæ must have more than a germ of truth in it.

According to Jeans, the primordial island universe begins as an immense chaotic mass of glowing gas, very nearly in the form of a sphere. As time goes on, and probably as a result of rotation, this sphere begins to flatten out, the nebulæ taking on the shape of a bun or a lens. After having spent some time in this flattening process, and having consumed some trillions of years in it, such a system will begin to show signs of internal disturbance. Disruptions and eruptions take place, and the nebula begins to throw up solid matter from the interior, spiral arms may develop, and even stars may appear on the outside. In a few more trillion years it may have gone through a complete transformation; from an amorphous-looking mass of gas it has become a real spiral. After the nebula has thus found its destination, the process of development appears to become more orderly. The spiral slowly unwinds its arms, opening and producing more stars. It goes through stages similar to those of the Andromeda nebula, and of the spirals in the Big Dipper

and in Triangulum, shown in Plate XV and XVI. Once started, it cannot stop the process of disintegration; it is doomed, and ultimately even the spiral arms disappear. Nothing is left now but a swarm of stars, a great star cloud, such as the Magellanic Clouds, and, in all probability, the Galactic system. From now on, it becomes possible that some of the more audacious stars begin wanderings of their own, leaving the mother universe and venturing forth in the depths of space. The majority of the stars will probably remain faithful to the main body, but it is now only a question of time as to how long they will manage to keep alive. The smaller stars die first, after having sent their light and heat into the insatiable cold of empty space. The larger stars follow, and finally the whole galaxy is reduced to a conglomeration of dying embers treading their *danse macabre* through the voids of creation and waiting to be gathered into the scrap heap of the cosmos, ultimately, perhaps, to be re-kindled.

Such is the drama of the evolution of an island universe as we now see it. With the aid of Jeans's theory and Hubble's observations we can scent the course of nebular evolution along an unmistakable path, looking into the past for hundreds of millions of years, and into space for sextillions of miles. For we must not forget that, in dealing with island universes, we are dealing, in Hubble's words, with a "history of receding horizons." If the light of

Photograph Mount Wilson Observatory

PLATE XVI

The spiral nebula in Triangulum, at a distance of 1,000,000 light years and about 20,000 light years in diameter. If removed to this distance the sun would appear about 1,000 times fainter than the faintest star on the plate. This island universe is on the verge of breaking up into individual stars and of losing its spiral character completely; it is probably not much younger than our Milky Way system.

the Andromeda nebula takes a million years to reach us, then we see this nebula, not as it is now, but as it was one million years ago. Even the nearest of all island universes, the Magellanic Clouds are seen only as they were 100,000 years ago, long before the last ice age on earth. The majority of island universes we observe in times far, far earlier than the appearance of man on earth.

From the scheme of evolution of a universe we may perhaps infer that island universes occupying the same stage of evolutionary progress are comparable in size. Basing our researches on this assumption, we can then make deductions concerning the relative frequency of each type of universe, and about the total number of galaxies in a given volume of space. In short, we can begin to study the population of that greater cosmos, the cosmos of island universes. One significant thing strikes us immediately; namely, that among all the different island universes now known there is not a single one that surpasses the Galactic system in size. They may all be more or less comparable to each other. The Andromeda nebula represents thus far the maximum dimensions, and even it, with its 50,000 light years diameter, is much inferior to our Galactic system, with its diameter of 300,000 light years. These extraneous stellar systems may all be island universes; our Milky Way system is still the only continent among them.

When the population of spiral nebulæ is studied in detail, it is soon noticed that "twin universes" are not uncommon; even whole clusters of universes have been observed, as, for example, the enormous cluster of spirals in Virgo and Coma Berenices, studied by Wolf, Lundmark, and Shapley. There appears to be little doubt, however, that this cluster is not a "super-universe," but rather an archipelago of sidereal coral reefs, perhaps mostly smaller than the Magellanic Clouds in size, and at a distance of some 10,000,000 light years. From the most recent data on island universes Hubble has calculated that they are on the average about 1,500,000 light years apart. Since the average size of these galaxies is probably not much more than 10,000 light years, it is obvious that island universes are not crowding each other, and that collisions between universes must be rather rare occurrences.

Another significant result of the island universe development is that it permits us to make an estimate of the size of the cosmos. According to relativity, the cosmos is not infinite, but finite in all directions. So far as man can see it and observe it as a universe of three dimensions, the cosmos must be limited in size. The new data on island universes indicate that the maximum size of this great cosmos is perhaps in the neighborhood of 100,000,000,000 light years. This does not mean that there is nothing beyond, but only that we terrestrials, living and thinking in three dimensions,

could never hope to observe it: "The fault is not in the stars, but in ourselves." Paradoxically, however, Einstein's theory does not state that we could see the end of the universe. Far from it. To us the universe must always *appear* unbounded, though it *is* finite. It is much the same way with us as with a flat ant crawling on the curved surface of a sphere. If the ant stays on the surface, it will never come to an end; it can crawl through eternity, and will never find that the surface of the sphere is bounded anywhere, yet it cannot get more than a certain distance away from its starting point. Half the circumference of the sphere would be this greatest distance, and if the ant were only able to perform measurements, it would find that the surface of the sphere is finite and equal to a perfectly definite amount of square inches. So it is with us; we live not on the curved surface of a sphere, but *in* a "curved space" in a universe which is finite yet unbounded. To the philosopher it may seem an extraordinary idea to try to limit the universe; the astronomer is not much disturbed by it, especially since he cannot, even with the most powerful telescopes at his disposal, penetrate into space deeper than one hundredth of the "greatest" distance.

What is the outcome of all this new information? Our giant telescopes have temporarily brushed aside the eternal veil of empty space, and in less than ten years we have advanced our milestones from 100,000 light years to 100,000,000, only to find

TABLE IV

Bricks of the Cosmos

From Proton and Electron to Einstein Universe

0.000,000,000,000,001	Proton.
0,000,000,000,000,1	Electron.
0.000,000,000,01	
0.000,000,001	
0.000,000,1	Hydrogen atom, 0.000,000,01.
0.000,01	Limit of microscopic vision.
0.001	Blood corpuscle 0.001.
0.1	
10	
1,000	Standard metre in Paris, 100.
100,000	Height of Woolworth Building, 26,000.
10,000,000	Summit of Mount Everest 900,000.
1,000,000,000	
100,000,000,000	Diameter of the earth, 1,274,000,000.
10,000,000,000,000	Diameter of the sun 139,000,000,000.
1,000,000,000,000,000	Distance sun-earth 14,945,000,000,000.
100,000,000,000,000,000	Diameter of the solar system.
10,000,000,000,000,000,000	Light year 1,000,000,000,000,000,000.
1,000,000,000,000,000,000,000	Distance of Sirius.
100,000,000,000,000,000,000,000	Most distant naked eye star. Diameter of the Milky Way system.
10,000,000,000,000,000,000,000,000	Distance of nearest spiral nebula.
1,000,000,000,000,000,000,000,000,000	Present telescopic penetration.
100,000,000,000,000,000,000,000,000,000	Einstein Universe.

From the smallest to the greatest, the size of the entire range of objects contained in the cosmos is here expressed in terms of the scientist's unit of length: the centimeter (0.4 inch).

that still more are awaiting us. The "eternal silence of infinite space" which so frightened Pascal has ceased to exist for us. Silence reigns no more in the realm of space, but has given way to a Babel of light messages from countless island universes, past, present, and future. Not content with a mere description of the material universe, we have gathered on our photographic plates a true record of the evolutionary drama of this universe, past and present. In a perhaps not entirely futile attempt to comprehend this time scale of the cosmos, we have fatigued our imagination to the breaking point, only to realize that in our apparent advance against infinity and eternity we never really gain ground. Our mind stands perplexed, our intellect overwhelmed, before the joint concept of infinity existing throughout eternity.

Chapter XVI

FROM CHAOS TO COSMOS

"We end, not with a period, but with a question mark."

—POINCARÉ.

IN OUR analysis of the astronomer's findings of the material universe we have perhaps not sufficiently stressed our gratitude to the eternal darkness of space. If the sun were always visible we might even now be completely ignorant of everything else in the universe; in the light of day it is as though seeing, we could not see, hearing, we could not understand. It is only the black and silent night, the perpetual gloom that pervades the chasms of infinity, that to us becomes the true torch and the true speech of science. Its very stillness is eloquent of that, it subdues a hostile universe, and makes audible the "voices of the past which speak to us from the depths of the vanished ages."

Our interpretation of the facts has been, I fear, a trifle too terrestrial. Let us therefore, in a final summary, again review the pageant of the stars, freed, if such be possible, from our human preju-

dices. To begin with, what is a star? A sphere of glowing gas, varying in size from a globe as small as the earth to one a thousand times larger than the sun in diameter, large enough almost to take in the entire orbit of Jupiter. In density such a mass of "gas" may vary from ten thousand times rarer than our atmosphere to several hundred thousand times denser than water. After a star comes a galaxy, which, when described in terms understandable on earth, would have to be called a vacuum. In taking the census of the Milky Way system, the best known of all galaxies, we find that the number of stars, when compared to the unfathomable stretches of space at their disposal, is so pitifully small that it is only equaled by the molecules of air when one cubic inch of normal air is allowed to expand over a cube of 150-miles side. Advancing still another step, we find that such a galaxy, though seemingly a vacuum when measured against terrestrial standards, represents a great condensation of matter in space: galaxies of sizes generally not more than 50,000 light years are parceled out at average distances of no less than 1,500,000 light years.

If for a moment we again have recourse to an illustration drawn from our inadequate terrestrial units, and liken the Milky Way system to something as small, *pro rata,* as the state of Massachusetts, we are effecting a reduction in the ratio of ten thousand million million to one. The Andro-

meda nebula, on this scale some thirty miles in size, would be slightly farther away than Washington, D. C.; the great spiral nebula in the Big Dipper perhaps as far as San Francisco. The Hawaiian Islands might appropriately represent the extended cluster of spiral nebulæ in Virgo, in distance as well as in size, although perhaps being somewhat deficient in number. The remotest galaxy within reach of the 100-inch telescope would perhaps be 60,000 miles distant, one fourth the distance from the moon, and the entire "Einstein Universe" would appear condensed within a space one eighth as large as the distance from the earth to the sun. Having reduced the cosmos to this state of helplessness in our imagination, even a ray of light must appear paralyzed: instead of 186,000 miles per second, it now moves at the sluggish rate of 3 feet per year. But our interest lies mainly in the Milky Way system, inside the state of Massachusetts in the above comparison. A vast assemblage of stars such as the globular cluster Omega Centauri has dwindled down to something comparable to the Harvard Stadium. The distance between the sun and the nearest star, four and one-half light years, has been reduced to thirteen feet, the sun itself to a particle only six one-millionth parts of an inch in diameter. If light appeared indolent to us on this small scale, we cannot be surprised to find the stars practically standing still; their average speed of 20 miles per

second has been annihilated, and they retain a velocity of only 4 inches in a thousand years.

As terrestrials we are not satisfied until we have put our earth in this picture. We may do so, but we shall never find it again: encircling the pin point that represents the sun, in a circle of just one thousandth of an inch in diameter, we find our earth, as a small, completely dark speck of matter one twentieth of one millionth of an inch in size. Our best microscopes could not possibly reveal it, and it would remain what it is to-day in the cosmos, an obscure, and infinitesimal nonentity, inhabited by phantom pygmies.

We have not yet finished. Our position of utter insignificance is made even more ignominious by the fact that what we, on earth, consider the usual aspect and the usual behavior of the universe are, in reality, features and conditions of extreme improbability. What to us are the essentials of existence are in the universe merely results of a fortuitous coincidence, and we may perhaps, defiantly, find comfort in the thought that we are freaks of nature.

We have already seen that "daylight" such as we enjoy for half the time, is an exceptional state of affairs. Throughout space darkness reigns, almost Stygian darkness, broken only by the feeble radiation of the distant stars. Within the confines of a galaxy such starlight may attain a total intensity of slightly less than 1 per cent. of the full

moon, about equal to that of a candle at a distance of fifty feet. In space at large, in the voids between galaxies, even this little is dimmed by distance, or by "fog" perhaps, and the total illumination might well be one thousand times less still.

We have likewise seen that the conditions that cause the birth of a planetary system must be of extremely rare occurrence, and that, therefore, our earth and the solar system, though in all probability not unique, must yet be regarded as reasonably uncommon in the realm of the cosmos.

On the surface of the earth the greater part of matter is in the liquid or solid state. In the stars matter is not only gaseous, but the high stellar temperatures have broken it up in simpler constituents, atoms, and electrons. Iron, on earth, is solid; in the universe at large it exists solely as vapor, and in this vapor in the form of mutilated atoms which have lost some of their electrons. Solid matter is an exceedingly rare occurrence, and it may well be that a large portion of all matter exists as protons and electrons.

The universe, as we now see it, is but a transient structure; it is dissipating its energy and mass without, so far as we can now ascertain, receiving anything in return. The sun is losing weight at the rate of one trillion tons per second; the whole Andromeda nebula is dissipating at least one billion times as much, and in two weeks loses as much mass as the whole earth weighs. Our own Milky Way

system is in all probability even more prodigal, and if we combine the radiations of all the galaxies in the cosmos, we find that, at the very least, a mass equal to that of our sun is being destroyed daily.

Here we have approached the Sphinx of modern science. The modern Œdipus who will solve her riddle has not yet risen, but, to draw the analogy closer, the ominous portents are already becoming apparent that, if he succeeds, it will only result in dire tragedy for his parents, the sciences of physics and astronomy. We must not forget, however, that no formulation of any law of the universe hitherto reached is certainly final; those laws found thus far by human science have to be modified continually. There is no special sanctity attached to the doctrine of relativity, or to the quantum theory. They do explain the great majority of physical facts now within our ken, but there can be no doubt that, at best, they are but imperfect portrayals of the real laws of nature, framed with human fallibility. In our description of the cosmos the truth of to-day is no more than an ephemeral phantom; it will turn into a falsehood when viewed in the light of the truth of to-morrow. In the last analysis the astronomer, and especially the cosmogonist, must abandon all positive assertions, and there is no need, therefore, to feel more than temporarily distressed by the logical and lamentably unavoidable conclusion of our present-day theories, so admirably voiced by Jeans in his sayings: "At

present the universe seems to be running down like a clock which no one winds up. . . . The widely desired cyclic universe, in which just as much matter is created as destroyed, would seem to be a universe already dead. . . . With universes, as with humanity, the only possible life is progress to the grave."

With this we enter the domain of the unknown, and approach that of metaphysics, and it is with true scientific reticence that the astronomer pauses on the threshold before presenting what might be termed his *credo;* for, unlike the metaphysician, the scientist does not try to divine a purpose behind it all—the scientist is satisfied with a descriptive explanation. After the portrait we have painted of the importance of the earth in the universe, and in view of the delicate balance needed between a multitude of diverse factors to produce and maintain human life, it would be superfluous to stress man's manifest insignificance in the material universe. Man's universe transcends the material; the reality of the immaterial takes its place beside the accepted existence of the material. In our studies of the material universe we may sometimes feel that we have lifted the veil that shrouds the mysteries of the empyrean, and reflect that the universe, so invincibly immense in size, may, after all, not be so invincible in conception. Having reached the portal of infinity, we, like Byron's Prometheus, "in portions may foresee

our own funereal destiny." In our contemplation of the immaterial we may then, freed from the bondage of our concepts of boundlessness and immortality to those of infinite extension and everlasting existence, feel that we have safely arrived at a point in our meditation from which we can ponder the enigma of infinity during the leisure of eternity.

NAME INDEX

NAME INDEX

SUBJECT INDEX

SUBJECT INDEX